# EVERYTHING SCIENCE

## GRADE 12 PHYSICAL SCIENCES

VERSION 1 CAPS

WRITTEN BY VOLUNTEERS

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# EVERYTHING SCIENCE

When we look outside at everything in nature, look around us at everything manufactured or look up at everything in space we cannot but be struck by the incredible diversity and complexity of life; so many things, that look so different, operating in such unique ways. The physical universe really contains incredible complexity.

Yet, what is even more remarkable than this seeming complexity is the fact that things in the physical universe are knowable. We can investigate them, analyse them and understand them. It is this ability to understand the physical universe that allows us to transform elements and make technological progress possible.

If we look back at some of the things that developed over the last century ñ space travel, advances in medicine, wireless communication (from television to mobile phones) and materials a thousand times stronger than steel we see they are not the consequence of magic or some inexplicable phenomena. They were all developed through the study and systematic application of the physical sciences. So as we look forward at the 21st century and some of the problems of poverty, disease and pollution that face us, it is partly to the physical sciences we need to turn.

For however great these challenges seem, we know that the physical universe is knowable and that the dedicated study thereof can lead to the most remarkable advances. There can hardly be a more exciting challenge than laying bare the seeming complexity of the physical universe and working with the incredible diversity therein to develop products and services that add real quality to peopleís lives.

Physical sciences is far more wonderful, exciting and beautiful than magic! It is everywhere.

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The merger between Metropolitan and Momentum was lauded for the complementary fit between two companies. This complementary fit is also evident in the focus areas of CSI programmes where Metropolitan and Momentum together cover and support the most important sectors and where the greatest need is in terms of social participation.

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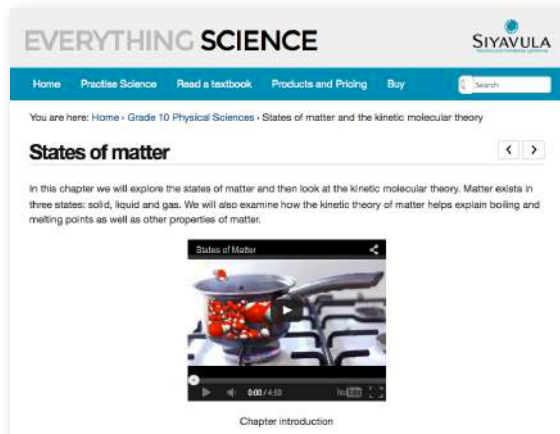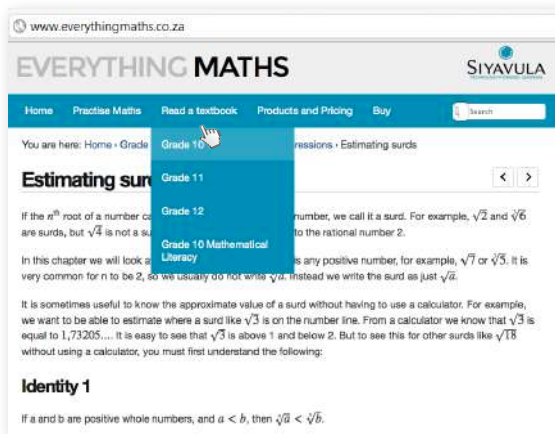
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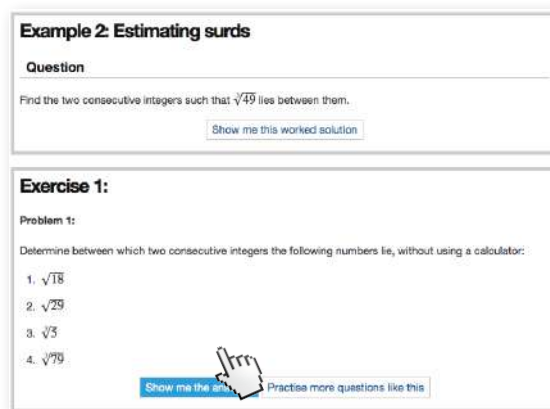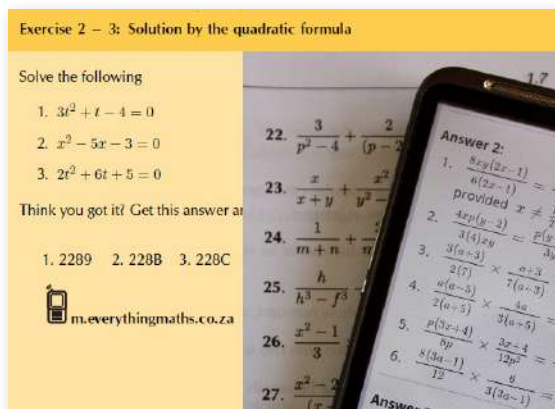
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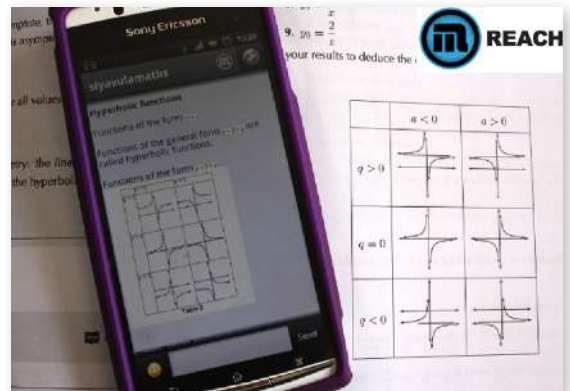
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# Contents

# CHAPTER

# *Skills for science*

This book deals with the physical sciences - physics and chemistry. All the sciences are based in the use of experiment and testing to understand the world around us better. The scientific method requires us to constantly re-examine our understanding, by testing new evidence with our current theories and making changes to those theories if the evidence does not meet the test. The scientific method therefore is the powerful tool you will use throughout the physical sciences.

Figure 1.1: An ultraviolet image of the Sun.

In this chapter you will learn how to gather evidence using the scientific method.

These skills will then be used throughout this textbook to test scientific theories and practices.

## 1.1 The development of a scientific theory ESCHQ

The most important, and most exciting, thing about science and scientific theories is that they are not fixed. Hypotheses are formed and carefully tested, leading to scientific theories that explain those observations and predict results. **The results are not made to fit the hypotheses**. If new information comes to light with the use of better equipment, or the results of other experiments, this new information is used to improve and expand current theories. If a theory is found to have been incorrect it is changed to fit this new information. The data should never be made to fit the theory, if the data does not fit the theory then the theory is reworked or discarded. Although this changing of opinion is often taken for inconsistency, it is this very willingness to adapt that makes science useful, and allows new discoveries to be made.

Remember that the term theory has a different meaning in science. A **scientific theory** is not like your theory of about why you can only ever find one sock. A scientific theory is one that has been tested and proven through repeated experiment and data. Scientists are constantly testing the data available, as well as commonly held beliefs, and it is this constant testing that allows progress, and improved theories.

### Gravity ESCHR

The theory of gravity has been slowly developing since the beginning of the 16th century. Galileo Galilei is credited with some of the earliest work. At the time it was widely believed that heavier objects accelerated faster toward the earth than light objects did. Galileo had a hypothesis that this was not true, and performed experiments to prove this.

Galileo's work allowed Sir Isaac Newton to hypothesise not only a theory of gravity on earth, but that gravity is what held the planets in their orbits. Newton's theory was used by John Couch Adams and Urbain Le Verrier to predict the planet Neptune in the solar system and this prediction was proved experimentally when Neptune was discovered by Johann Gottfried Galle.

Although a large majority of gravitational motion could be explained by Newton's theory of gravity, there were things that did not fit. But although a newer theory that better fits the facts was eventually proved by Albert Einstein, Newton's gravitational theory is still successfully used in many applications where the masses, speeds and energies are not too large.

**FACT**
Robert Boyle should be a familiar name to you. Boyle's law came about from his air pump experiments, where he discovered that pressure is inversely proportional to volume at a constant temperature ($p \propto \frac{1}{V}$ at constant T).

## Thermodynamics ESCHS

The principles of the three rules of thermodynamics describe how energy works, on all size levels (from the workings of the Earth's core, to a car engine). The basis for these three rules started as far back as 1650 with Otto von Guericke. He had a hypothesis that a vacuum pump could be made, and proved this by making one. In 1656 Robert Boyle and Robert Hooke used this information and built an air pump.

Over the next 150 years the theory was expanded on and improved. Denis Papin built a steam pressuriser and release valve, and designed a piston cylinder and engine, which Thomas Savery and Thomas Newcomen built. These engines inspired the study of heat capacity and latent heat. Joseph Black and James Watt increased the steam engine efficiency and it was their work that Sadi Carnot (considered the father of thermodynamics) studied before publishing a discourse on heat, power, energy and engine efficiency in 1824.

This work by Carnot was the beginning of modern thermodynamics as a science, with the first thermodynamics textbook written in 1859, and the first and second laws of thermodynamics being determined in the 1850s. Scientists such as Lord Kelvin, Max Planck, J. Willard Gibbs (all names you should recognise) among many many others studied thermodynamics. Over the course of 350 years thermodynamics has developed from the building of a vacuum pump, to some of the most important fundamental laws of energy.

# 1.2 Scientific method ESCHT

The scientific method is the basic skill process in the world of science. Since the beginning of time humans have been curious as to why and how things happen in the world around us. The scientific method provides scientists with a well structured scientific platform to help find the answers to their questions. Using the scientific method there is no limit as to what we can investigate. The scientific method can be summarised as follows:

1. Ask a question about the world around you.
2. Do background research on your questions.
3. Make a hypothesis about the event that gives a sensible result. You must be able to test your hypothesis through experiment.
4. Design an experiment to test the hypothesis. These methods must be repeatable and follow a logical approach.
5. Collect data accurately and interpret the data. You must be able to take measurements, collect information, and present your data in a useful format (drawings, explanations, tables and graphs).
6. Draw conclusions from the results of the experiment. Your observations must be made objectively, never force the data to fit your hypothesis.
7. Decide whether your hypothesis explains the data collected accurately.
8. If the data fits your hypothesis, verify your results by repeating the experiment or getting someone else to repeat the experiment.
9. If your data does not fit your hypothesis perform more background research and

**FACT**
In science we never 'prove' a hypothesis through a single experiment because there is a chance that you made an error somewhere along the way. What you can say is that your results SUPPORT the original hypothesis.

make a new hypothesis.

Remember that in the development of both the gravitational theory and thermodynamics, scientists expanded on information from their predecessors or peers when developing their own theories. It is therefore very important to communicate findings to the public in the form of scientific publications, at conferences, in articles or TV or radio programmes. It is important to present your experimental data in a specific format, so that others can read your work, understand it, and repeat the experiment.

1. Aim: A brief sentence describing the purpose of the experiment.
2. Apparatus: A list of the apparatus.
3. Method: A list of the steps followed to carry out the experiment.
4. Results: Tables, graphs and observations about the experiment.
5. Discussion: What your results mean.
6. Conclusion: A brief sentence concluding whether or not the aim was met.

**A hypothesis**

A hypothesis should be specific and should relate directly to the question you are asking. For example if your question about the world was, why do rainbows form, your hypothesis could be: *Rainbows form because of light shining through water droplets*. After formulating a hypothesis, it needs to be tested through experiment. An incorrect prediction does not mean that you have failed. It means that the experiment has brought some new facts to light that you might not have thought of before.

**Activity: Analysis of the scientific method.**
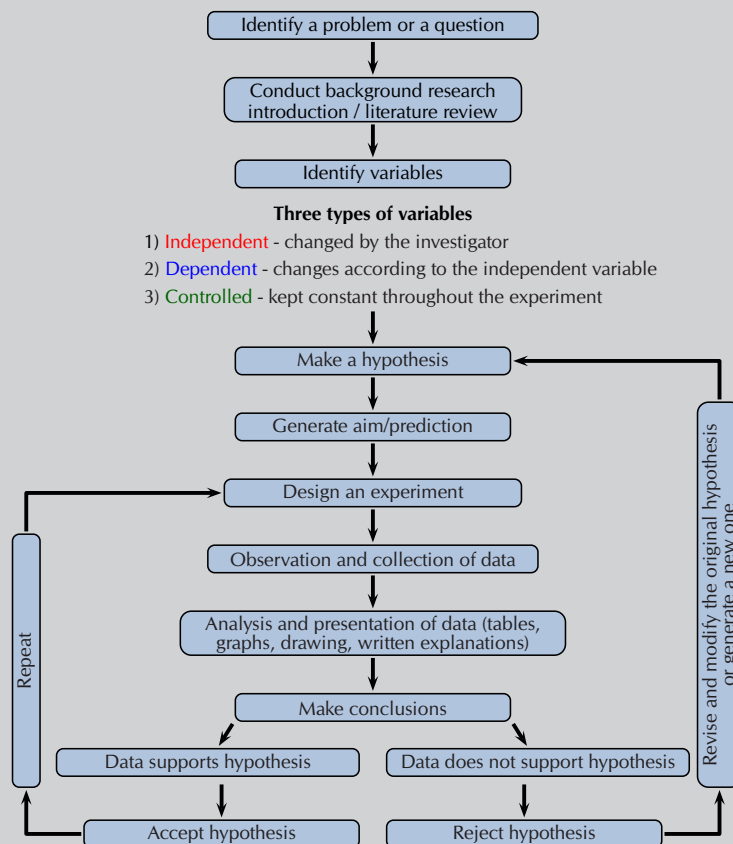
Figure 1.2: Overview of scientific method.

Break into groups of 3 or 4 and study the flow diagram provided, then discuss the questions that follow.

1. Once you have a problem you would like to study, why is it important to conduct background research before doing anything else?
2. What is the difference between a dependent, independent, and controlled variable and why is it important to identify them?
3. What is the difference between identifying a problem, a hypothesis, and a scientific theory?
4. Why is it important to repeat your experiment if the data fits the hypothesis?

**Activity: Designing your own experiment**

Recording and writing up an investigation is an integral part of the scientific method. In this activity you are required to design your own experiment. Use the information provided below, and the flow diagram in the previous experiment to help you design your experiment.

The experiment should be handed in as a 1 - 2 page report. Below are basic steps to follow when designing your own experiment.

1. Ask a question which you want to find an answer to.
2. Perform background research on your topic of choice.
3. Write down your hypothesis.
4. Identify variables important to your investigation: those that are relevant, those you can measure or observe.
5. Decide on the independent and dependent variables in your experiment, and those variables that must be kept constant.
6. Design the experiment you will use to test your hypothesis:
    - State the aim of the experiment.
    - List the apparatus (equipment) you will need to perform the experiment.
    - Write the method that will be used to test your hypothesis
        - in bullet format
        - in the correct sequence, with each step of the experiment numbered.
    - Indicate how the results should be presented, and what data is required.

## Reading instruments ESCHV

Before you perform an experiment you should be comfortable with certain apparatus that you will be using. The following pages give some commonly used apparatus and how to use them.

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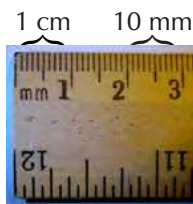


Figure 1.3: The end of a ruler.

Most rulers you find have two sets of lines on them. You can ignore those with the numbers spaced further apart. We only work in the metric system and those are for the imperial system. The closest together lines are for millimetres, the thicker lines are for 5 mm and the thicker, longer lines with numbers next to them mark off every 10 mm (1 cm).

A thermometer can have one, or two sets of numbers on it. If it has two sets of numbers one will be in Celsius, and one will be in Fahrenheit. We use Celsius, so you can ignore the side with a larger temperature range. In Figure 1.4 you can ignore the right-hand side. Looking on the left you can see that the red line (coloured ethanol here) is next to the fourth line above 0 °C. Each small line is 1 °C, so the temperature is 4 °C.

Figure 1.4: Reading a thermometer.

Laboratory thermometers will go to much higher temperatures than those used for measuring the temperature outside, or your body temperature. It is important to make sure that the thermometer you are using can handle the temperature you will be measuring too. If not, do not use that thermometer as you will break it. Make sure your thermometer is upright whenever you use it in an experiment, to avoid incorrect results.

Figure 1.5: A laboratory style thermometer.

See video: 27HM at www.everythingscience.co.za

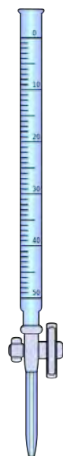
Different scales have different functions. However, a basic function of all scales is a **tare** button. This zeros the balance. It is important that you zero the balance before you take any measurements. If you are weighing something on a piece of paper you should tare the balance with the piece of paper on it, and weigh the substance. Make sure you check the units that your scale is weighing in. If you want your value to be accurate to ,00 g then the scale must measure to that accuracy. A scale that measures in mg would be best.

Figure 1.6: A scale (also referred to as a balance).

The surface of the water (the *meniscus*) is slightly higher at the edges of a container than in the middle. This is due to surface tension and the interaction between the water and the edge of the container (Figure 1.7). When measuring the volume in a burette or measuring cylinder or pipette you should look at the bottom of the meniscus. Where that lies is where you measure the volume. So in this example the meniscus is on the fifth line below the large line that represents 1 ml. Therefore the volume is 1,5 ml.

It is also possible that the liquid being measured has greater internal forces than those between it and the container. Then the meniscus would be higher in the middle than at the sides, and you would use the top of the meniscus to measure your volume.

Figure 1.7: The meniscus of water in a burette.

Figure 1.8: A burette.

A burette is used to accurately measure the volume of a liquid added in an experiment. The valve at the bottom allows the liquid to be added drop-by-drop, and the initial and final volume can be measured so that the total volume added is known. More information about burettes is given to you in your first titration experiment this year in Chapter 9.

A measuring cylinder is used to measure volumes that you want accurate to the nearest millilitre or so. It is not a highly accurate way of measuring volumes. The volume in a measuring cylinder is measured in the same way as for a burette, the difference is that in a measuring cylinder the smallest volume would be at the bottom, while the largest would be at the top.

Figure 1.9: A measuring cylinder with water.

There are two types of pipettes you might encounter this year. A volumetric pipette has a large bulb, marked with the set volume it can measure. Above the bulb on these pipettes there is a line. For a 5 ml volumetric pipette, when the meniscus of your liquid sits on the line, then the volume in that pipette is 5 ml.

A graduated pipette has the same type of marking you see on a burette. The top is 0 ml, and the volume increases as you move down the pipette. In this pipette you should fill the pipette to near the 0 ml line and make a note of the volume. You can then add the desired volume, stopping when the volume in the pipette has decreased by the required amount.

Figure 1.10: A 5 ml volumetric pipette.

Figure 1.11: A graduated pipette.

A learner wondered whether the rate of evaporation of a substance was related to the boiling point of the substance. Having done background research they realised that the boiling point of a substance is linked to the intermolecular forces within the substance. They know that greater intermolecular forces require more energy to overcome. This led them to form the following hypothesis:

*The larger the intermolecular forces of a substance the higher the boiling point. Therefore, if a substance has higher boiling point it will have a slower rate of evaporation.*

Perform the following experiment that the learner designed to test that hypothesis.

**Experiment: Boiling points and rate of evaporation: Part 1**

**Aim:**

To determine whether the rate of evaporation of a substance is related to its boiling point.

**Apparatus:**

You will need the following items for this experiment:

- 220 ml water, 20 ml methylated spirits, 20 ml nail polish remover, 20 ml water, 20 ml ethanol
- One 250 ml beaker, four 20 ml beakers, a thermometer, a stopwatch or clock

**Method:**

**WARNING!**

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**All alcohols are toxic, methanol is particularly toxic and can cause blindness, coma or death. Handle all chemicals with care.**

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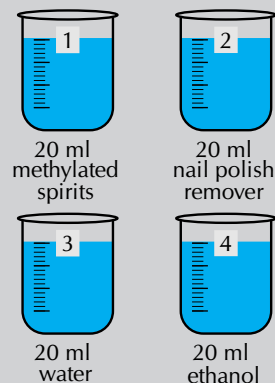
1. Place 200 ml of water into the 250 ml beaker and move the beaker to sunny spot. Place the thermometer in the water.
2. Label the four 20 ml beakers **1** - **4**. These beakers should be marked.
3. Place 20 ml methylated spirits into beaker 1, 20 ml nail polish remover into beaker 2, 20 ml water into beaker 3 and 20 ml ethanol into beaker 4.
4. Carefully move each beaker to the warm (sunny) spot.
5. Observe each dish every two minutes. Note the volume in the beaker each time.
6. Continue making observations for 20 minutes. Record the volumes in a table.

**Results:**

- Record your observations from the investigation in a table like the one below.

| Substance | Methylated spirits | Nail polish remover | Water | Ethanol |
|---|---|---|---|---|
| **Boiling point (°C)** | 78,5 | 56,5 | 100 | 78,4 |
| **Initial volume (ml)** | 20 | 20 | 20 | 20 |
| **2 min** | | | | |
| **4 min** | | | | |
| **6 min** | | | | |

## 1.3 Data and data analysis ESCHX

In order to analyse the data obtained during experiments it is often necessary to convert that data into different representations. One type of representation is a graph. A few examples are given here.

### How to draw graphs in science ESCHY

For all graphs plotted from experimental data it is important to remember that you should never *connect the dots*. Data will never follow a line or curve perfectly. By obtaining multiple experimental data points any discrepancies in each data point can be removed. The line added after the points are plotted should be a **best fit line** that can then be used to more accurately determine further information.

Features of graphs you plot:

- An appropriate scale is used for each axis so that the plotted points use most of the axis/space (work out the range of the data and the highest and lowest points).
- The scale must **remain the same** along the entire axis and should use easy intervals such as 10's, 20's, 50's. Use graph paper for accuracy.
- Each axis must be labelled with what is shown on the axis and must include the appropriate units in brackets, e.g. Temperature (°C), time (seconds), height (cm).
- The independent variable is generally plotted along the x-axis, while the dependent variable is generally plotted along the y-axis.
- Each point has an x and y co-ordinate and is plotted with a symbol which is big enough to see, e.g. a cross or circle.
- A best fit line is then added to the graph.
- **Do not** start the graph at the origin unless there is a data point for (0,0), or if the best fit line runs through the origin.
- The graph must have a clear, descriptive title which outlines the relationship between the dependent and independent variable.
- If there is more than one set of data drawn on a graph, a different symbol (and/or colour) must be used for each set and a key or legend must define the symbols.
- Use line graphs when the relationship between the dependent and independent variables is continuous.
- For a line graph, you can draw a line of best fit with a ruler. The number of points are distributed fairly evenly on each side of the line (see Figure 1.12).
- With an exponential graph (when the points appear to be following a curve) you can draw a best fit line freehand (see 1.13).

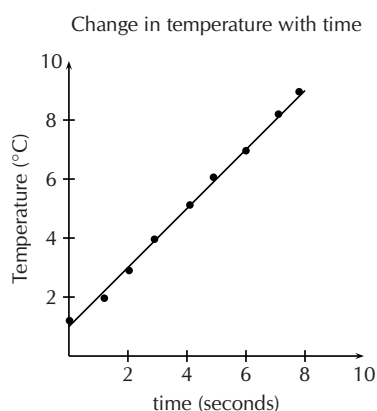



Figure 1.12: A straight line graph of the change in temperature with time.

Change in distance (due to acceleration) with time

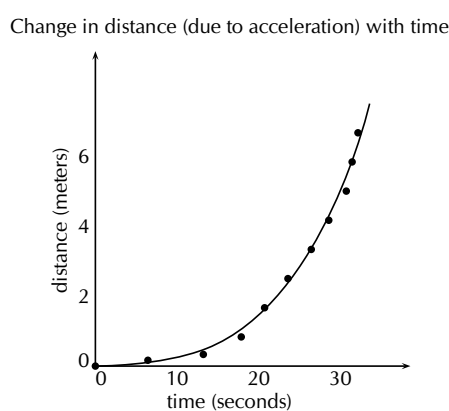



Figure 1.13: A graph with an exponential best fit line.

Remember that without units much of our work as scientists would be meaningless. We need to express our thoughts clearly and units give meaning to the numbers we measure and calculate. Depending on which units we use, the numbers are different. For example if you have 12 water, it means nothing. You could have 12 ml of water, 12 litres of water, or even 12 bottles of water. Units are an essential part of the language we use. Units must be specified when expressing physical quantities.

## Qualitative and quantitative analysis ESCHZ

### Qualitative analysis

In **qualit**ative research you look at the quality of a substance. At how it looks compared to other cases. You do an in-depth analysis of a specific case, and then make an informed decision about similar cases.

For example, a qualitative study of the study habits of university students could include only a few people, or over twenty. Each person would be asked in-depth questions about how they study, and what works for them, and a general, informed assertion can then be made about these study habits.

### Quantitative analysis

In **quantit**ative research you look at specific numbers. You study a large group (data sample) and do statistical analyses of the group, with experimental controls, manipulation of variables, and the modelling and analysis of your data.

For example, a quantitative study of those same study habits of university students would include a large number of people, for statistical relevance. The questions asked would include raw data of actual studying hours, and the most productive study times. These data points would then be analysed using graphical models.

**Experiment: Boiling points and rate of evaporation: Part 2**

**Results:**

Now that you remember how to plot graphs, go back to the data you obtained during the previous experiment.

- On the same set of axes, plot a graph of the volume (ml) versus the time (min) for each substance.

**Analysis of results or discussion:**

- Analyse the results plotted on the graphs and the table.
- Which substance has the fastest decrease in volume? Which has the slowest decrease?
- Discuss if there are any relationships between your independent (time) and dependent (volume) variables (what type of graph did you plot?).
- It is important to look for patterns/trends in your graphs or tables and describe these clearly in words.
- Compare the different graphs and the different rates of evaporation to the boiling points of the substances.

**Evaluation of results:**

- This is where you answer the question *Is the rate of evaporation of a substance related to its boiling point?*
- You need to carefully consider the results:

- Were there any unusual results? If so then these should be discussed and possible reasons given for them.
- Discuss how you ensured the validity and reliability of the investigation. Was it a fair test (validity) and if the experiment were to be repeated would the results obtained be similar (reliability)? The best way to ensure reliability is to repeat the experiment several times and obtain an average.
- Discuss any experimental errors that may have occurred during the experiment. These can include errors in the methods and apparatus. Make suggestions on what could be done differently next time.
- Did this experiment yield qualitative or quantitative results?

## Conclusions based on scientific evidence ESCJ2

**Experiment: Boiling points and rate of evaporation: Part 3**

**Conclusion:**

You have your results, and the analysis of your results. Now you need to look back at your hypothesis.

The conclusion needs to link the results to the aim and hypothesis. In a short paragraph, write down if what was observed supports or reject the hypothesis. If your original hypothesis does not match up with the final results of your experiment, do not change the hypothesis. Instead, try to explain what might have been wrong with your original hypothesis. What information did you not have originally that caused you to be wrong in your prediction.

**Activity: Conclusions and bias**

Read the following extract on bias taken from radiology.rsna.org (01/09/13), and answer the questions that follow:

> *Bias is a form of systematic error that can affect scientific investigations and distort the measurement process. A biased study loses validity in relation to the degree of the bias. While some study designs are more prone to bias, its presence is universal. It is difficult or even impossible to completely eliminate bias. In the process of attempting to do so, new bias may be introduced or a study may be rendered less generalizable. Therefore, the goals are to minimize bias and for both investigators and readers to comprehend its residual effects, limiting misinterpretation and misuse of data.*

- In the light of the above quotation, why is it important for you to clearly state all your experimental parameters?
- Why is it important never to try and make the data fit your hypothesis?
- Look again at the conclusions you drew during your experiment.
  - Are they biased?
  - Did you make any assumptions based on preconceived ideas?
  - Is the data presented in a clear way that does not force a reader to agree with your conclusions?

**Activity: Different explanations for the same set of experimental data.**

To prevent bias, it is important to be able to look at the same information in different ways, to make sure your conclusion is the most logical one.

Divide into groups of three or four and compare the conclusions you drew from the boiling points and rate of evaporation experiment, and answer the questions that follow:

- Did anyone in the group draw a different conclusion from the one you drew? If yes, discuss the merits and short-falls of the different conclusions.
- Did your conclusion match what you were expecting to find from the hypothesis?
- Can you think of any other explanation that would explain your data?

**Activity: Methods of knowing used by non-scientists.**

Research one of the following topics and report your findings to the class in a five minute oral presentation:

- Traditional medicines.
- Navigation and knowledge of the seasons, from the stars.

### Designing a model ESCJ3

Sometimes a system is too large to be studied, or too difficult to recreate experimentally. In these cases it is possible to design a model based on a smaller system, that fits the data observed for the larger system. Here are some key points to remember when designing a model:

- A model is a testable idea that describes a large system that is not easily testable.
- The model should be able to explain as many observations of the large system as possible, and yet be relatively simple.

An example of a model was the spherical model of the Earth, rather than a flat one.

- Many educated people of the day (in the late 1400s) knew that the Earth could not be flat due to observations that did not fit. A spherical Earth model was proposed, which was testable on a small scale.
- The model explained many previously unexplained phenomenon (such as that ships appeared to *sink* over the horizon, regardless of the direction of travel).
- The model was further verified by the shape of the Earth's shadow on the moon during lunar eclipses.

## 1.4 Laboratory safety procedures ESCJ4

Laboratories have rules that are enforced as safety precautions. These rules are:

- Before doing any scientific experiment make sure that you know where the fire extinguishers are in your laboratory and there should also be a bucket of sand to extinguish fires.
- You are responsible for your own safety as well as the safety of others in the laboratory. Never perform experiments alone.

- Do not eat or drink in the laboratory. Do not use laboratory glassware to eat or drink from.
- Ensure that you are dressed appropriately whenever you are near chemicals:
  - hair tied back
  - no loose or flammable clothing
  - closed shoes
  - gloves
  - safety glasses
- Always behave responsibly in the laboratory. Do not run around or play practical jokes. Always check the safety data of any chemicals you are going to use. Never smell, taste or touch chemicals unless instructed to do so. Do not take chemicals from the laboratory.
- Only perform the experiments that your teacher instructs you to. Never mix chemicals for fun. Follow the given instructions exactly. Do not mix up steps or try things in a different order.
- Care needs to be taken when pouring liquids or powders from one container to another. When spillages occur you need to call the teacher immediately to assist in cleaning up the spillage.
- Care needs to be taken when using strong acids and bases. A good safety precaution is to have a solution of sodium bicarbonate in the vicinity to neutralise any spills as quickly as possible. If you spill on yourself wash the area with lots of water and seek medical attention. Never add water to acid. Always add the acid to water.
- When working with chemicals and gases that are hazardous, a fume cupboard should be used. Always work in a well ventilated area.
- When you are instructed to smell chemicals, place the container on a laboratory bench and use your hand to gently waft (fan) the vapours towards you.
- Be alert and careful when handling chemicals, hot glassware, etc. Never heat thick glassware as it will break. (For example, do not heat measuring cylinders).
- When lighting a Bunsen burner the correct procedure needs to be followed: securely connect the rubber tubing to the gas pipe, have your matches ready, turn on the gas, then light a match and the bunsen burner. Do not leave Bunsen burners and flames unattended.
- When heating substances in a test tube do not overheat the solution. Remember to face the mouth of the test tube away from you and members of your group when heating a test tube.
- Always check with your teacher how to dispose of waste. Chemicals should not be disposed of down the sink.
- Ensure all Bunsen burners are turned off at the end of the practical and all chemical containers are sealed.

## Hazard data ESCJ5

Before starting any experiment, research the chemicals and materials you will be using in that experiment. Laboratory chemicals can be dangerous, and you should study the safety data sheets should before working with a chemical. The data sheets can be found at http://www.msds.com/.

Before working with a chemical, you should also make sure that you know how to, and have the facilities available to, dispose of those chemicals correctly and safely. Many chemicals cannot simply be washed down the sink. If you follow these few simple guidelines you can safely carry out experiments in the laboratory without endangering yourself or others around you.

CHAPTER

# Momentum and impulse

## 2.1 Introduction ESCJ6

In Grade 10 we studied motion but not what caused the motion, in Grade 11 we learnt about forces and how they can alter the motion of an object. In this chapter we will focus on what happens when two bodies undergo a contact interaction and how their motion is affected. We learn more about how force and motion are related. We are introduced to two new concepts, momentum and impulse.

We can begin by considering some scenarios to set the context. Most people have some intuition for physics based on their everyday experiences but they haven't formalised it. We can use our intuitive answers to lead into more structured thinking about physical events.

Everyone has experienced a mosquito landing on their arm and it can happen quite unnoticed. Consider the case of a falcon landing on your arm (ignore the sharp claws for now). You would definitely notice, why? What makes a mosquito different to a falcon? Would you still notice if the mosquito flew the same way as a falcon, or if the falcon copied the flight of a mosquito before landing? You probably would still notice, but try to think about what makes them so different.

Look at a motorcycle, motorcar and truck. Which of them is more likely to result in less damage in a collision situation, why? What factors would you change to reduce potential damage.

The factors that come up in these considerations are how fast things are moving and how massive they are. A falcon moving at the same speed as a mosquito still has a much larger mass. Even if a mosquito moved as fast as a falcon it wouldn't bother us because the mass of a mosquito is so small.

If a motorcycle, motorcar and truck were all moving at the same speed then it would be much safer to be in a collision with the motorcycle but a truck doesn't have to be moving as fast as a motorcycle to have a huge impact in a collision because of its large mass.

Why is the Moon's orbit largely unaffected when it is hit by asteroid?

**TIP**
Momentum transfer doesn't require a contact interaction but we won't consider any non-contact scenarios in this chapter.

There is an interplay between mass and speed (velocity to be precise) that governs what would happen if these objects came into contact with another object. There are two quantities that depend on mass and velocity, kinetic energy and momentum. Kinetic energy is something that we learnt about previous. Momentum is different to kinetic energy and is what we will focus on in the first part of this chapter. In the second part we will cover some of the differences between kinetic energy and momentum.

**Key linked concepts**

- Units and unit conversions — Physical Sciences, Grade 10, Science skills
- Equations — Mathematics, Grade 10, Equations and inequalities
- Techniques of vector addition — Physical Sciences, Grade 10, Vectors and scalars
- Newton's laws — Physical Sciences, Grade 11, Forces

## 2.2 Momentum ESCJ7

Momentum is a physical quantity which is closely related to forces. Momentum is a property which applies to moving objects, in fact it is mass in motion. If something has mass and it is moving then it has momentum.

**DEFINITION:** *Momentum*

The linear momentum of a particle (object) is a vector quantity equal to the product of the mass of the particle (object) and its velocity.

The momentum (symbol $\vec{p}$) of an object of mass $m$ moving at velocity $v$ is: $\vec{p} = m\vec{v}$

Momentum is directly proportional to both the mass and velocity of an object. A small car travelling at the same velocity as a big truck will have a smaller momentum than the truck. The smaller the mass, the smaller the momentum for a fixed velocity. If the mass is constant then the greater the velocity the greater the momentum. The momentum will always be in the same direction as the velocity because mass is a scalar not a vector.

### Vector nature of momentum ESCJ8

A car travelling at 120 $km{\cdot}hr^{-1}$ will have a larger momentum than the same car travelling at 60 $km{\cdot}hr^{-1}$. Momentum is also related to velocity; the smaller the velocity, the smaller the momentum.

Different objects can also have the same momentum, for example a car travelling slowly can have the same momentum as a motorcycle travelling relatively fast. We can easily demonstrate this.

**TIP**
A vector multiplied by a scalar has the same direction as the original vector but a magnitude that is scaled by the multiplicative factor.

Consider a car of mass 1000 kg with a velocity of 8 m·s$^{-1}$ (about 30 km·hr$^{-1}$) East. The momentum of the car is therefore:

$$\begin{aligned}\vec{p} &= m\vec{v}\\ &= (1000)\,(8)\\ &= 8000\ \text{kg·m·s}^{-1}\ \text{East}\end{aligned}$$

Now consider a motorcycle, also travelling East, of mass 250 kg travelling at 32 m·s$^{-1}$ (about 115 km·hr$^{-1}$). The momentum of the motorcycle is:

$$\begin{aligned}\vec{p} &= m\vec{v}\\ &= \left(250\ \text{kg}\right)\left(32\ \text{m·s}^{-1}\right)\\ &= 8000\ \text{kg·m·s}^{-1}\ \text{East}\end{aligned}$$

Even though the motorcycle is considerably lighter than the car, the fact that the motorcycle is travelling much faster than the car means that the momentum of both vehicles is the same.

From the calculations above, you are able to derive the unit for momentum as kg·m·s$^{-1}$.

Momentum is also vector quantity, because it is the product of a scalar ($m$) with a vector ($\vec{v}$).

This means that whenever we calculate the momentum of an object, we should include the direction of the momentum.

See video: 27HN at www.everythingscience.co.za

**Worked example 1: Momentum of a soccer ball**

***QUESTION***

A soccer ball of mass 420 g is kicked at 20 m·s$^{-1}$ towards the goal post. Calculate the momentum of the ball.

***SOLUTION***

**Step 1: Identify what information is given and what is asked for**
The question explicitly gives:

- the mass of the ball, and
- the velocity of the ball.

The mass of the ball must be converted to SI units. 420 g = 0,42 kg

We are asked to calculate the momentum of the ball. From the definition of momentum, $\vec{p} = m\vec{v}$ we see that we need the mass and velocity of the ball, which we are given.

**Step 2: Do the calculation**

We calculate the magnitude of the momentum of the ball,

$$\begin{aligned}\vec{p} &= m\vec{v}\\ &= (0,42)(20)\\ &= 8,40 \text{ kg}\cdot\text{m}\cdot\text{s}^{-1}\end{aligned}$$

**Step 3: Quote the final answer**

We quote the answer with the direction of motion included, $\vec{p} = 8,40$ kg·m·s$^{-1}$ in the direction of the goal post.

**Worked example 2: Momentum of a cricket ball**

***QUESTION***

A cricket ball of mass 160 g is bowled at 40 m·s$^{-1}$ towards a batsman. Calculate the momentum of the cricket ball.

***SOLUTION***

**Step 1: Identify what information is given and what is asked for**

The question explicitly gives

- the mass of the ball ($m = 160$ g $= 0,16$ kg), and
- the velocity of the ball ($\vec{v} = 40$ m·s$^{-1}$ towards the batsman)

To calculate the momentum we will use $\vec{p} = m\vec{v}$.

**Step 2: Do the calculation**

$$\begin{aligned}\vec{p} &= m\vec{v}\\ &= (0,16)(40)\\ &= 6,4 \text{ kg}\cdot\text{m}\cdot\text{s}^{-1}\\ &= 6,4 \text{ kg}\cdot\text{m}\cdot\text{s}^{-1} \text{ in the direction of the batsman}\end{aligned}$$

**Step 3: Quote the final answer**

The momentum of the cricket ball is 6,4 $\text{kg}\cdot\text{m}\cdot\text{s}^{-1}$ in the direction of the batsman.

**Worked example 3: Momentum of the Moon**

***QUESTION***

The centre of the Moon is approximately 384 400 km away from the centre of the Earth and orbits the Earth in 27,3 days. If the Moon has a mass of $7{,}35 \times 10^{22}$ kg, what is the magnitude of its momentum (using the definition given in this chapter) if we assume a circular orbit? The actual momentum of the Moon is more complex but we do not cover that in this chapter.

***SOLUTION***

**Step 1: Identify what information is given and what is asked for**

The question explicitly gives

- the mass of the Moon ($m = 7{,}35 \times 10^{22}$ kg)
- the distance to the Moon (384 400 km = 384 400 000 m = $3{,}844 \times 10^{8}$ m)
- the time for one orbit of the Moon (27,3 days = $27{,}3 \times 24 \times 60 \times 60 = 2{,}36 \times 10^{6}$ s)

We are asked to calculate only the magnitude of the momentum of the Moon (i.e. we do not need to specify a direction). In order to do this we require the mass and the magnitude of the velocity of the Moon, since $\vec{p} = m\vec{v}$.

**Step 2: Find the magnitude of the velocity of the Moon**

The magnitude of the average velocity is the same as the speed. Therefore: $v = \frac{\Delta x}{\Delta t}$

We are given the time the Moon takes for one orbit but not how far it travels in that time. However, we can work this out from the distance to the Moon and the fact that the Moon has a circular orbit.

Using the equation for the circumference, C, of a circle in terms of its radius, we can determine the distance travelled by the Moon in one orbit:

$$\begin{aligned} C &= 2\pi r \\ &= 2\pi\left(3{,}844 \times 10^8\right) \\ &= 2{,}42 \times 10^9 \text{ m} \end{aligned}$$

Combining the distance travelled by the Moon in an orbit and the time taken by the Moon to complete one orbit, we can determine the magnitude of the Moon's velocity or speed,

$$\begin{aligned} v &= \frac{\Delta x}{\Delta t} \\ &= \frac{C}{T} \\ &= \frac{2{,}42 \times 10^9 m}{2{,}36 \times 10^6 s} \\ &= 1{,}02 \times 10^3 \text{ m·s}^{-1}. \end{aligned}$$

**Step 3: Finally calculate the momentum and quote the answer**

The magnitude of the Moon's momentum is:

$$\begin{aligned} \vec{p} &= m\vec{v} \\ p &= mv \\ &= \left(7{,}35 \times 10^{22}\right)\left(1{,}02 \times 10^3\right) \\ &= 7{,}50 \times 10^{25} \text{ kg·m·s}^{-1} \end{aligned}$$

The magnitude of the momentum of the Moon is $7{,}50 \times 10^{25}$ kg·m·s$^{-1}$.

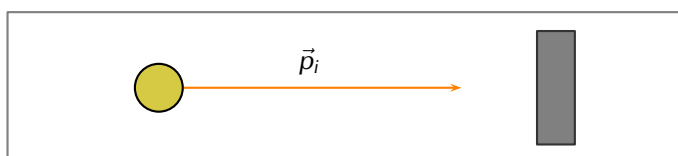
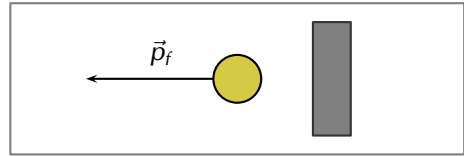
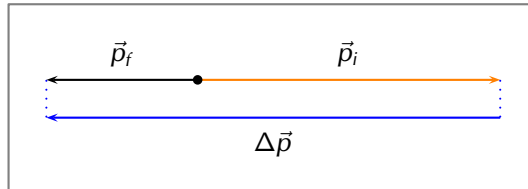
As we have said, momentum is a vector quantity. Since momentum is a vector, the techniques of vector addition discussed in Vectors and scalars in Grade 10 must be used when dealing with momentum.

## Change in momentum ESCJ9

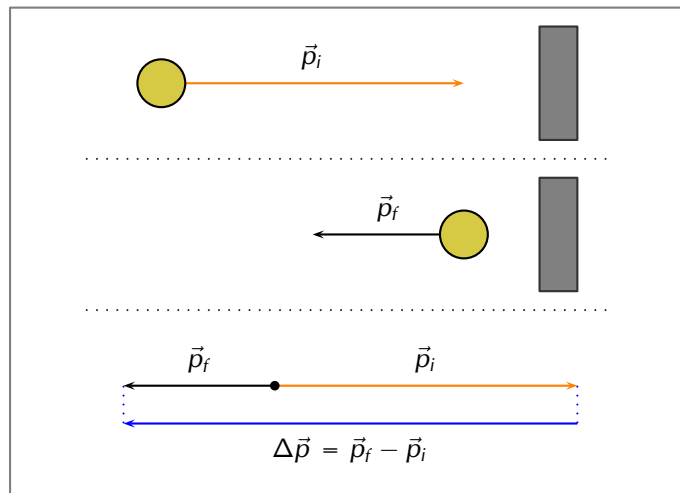
Particles or objects can collide with other particles or objects, we know that this will often change their velocity (and maybe their mass) so their momentum is likely to change as well. We will deal with collisions in detail a little bit later but we are going to start by looking at the details of the change in momentum for a single particle or object.

**Case 1: Object bouncing off a wall**

Lets start with a simple picture, a ball of mass, $m$, moving with initial velocity, $\vec{v}_i$, to the right towards a wall.

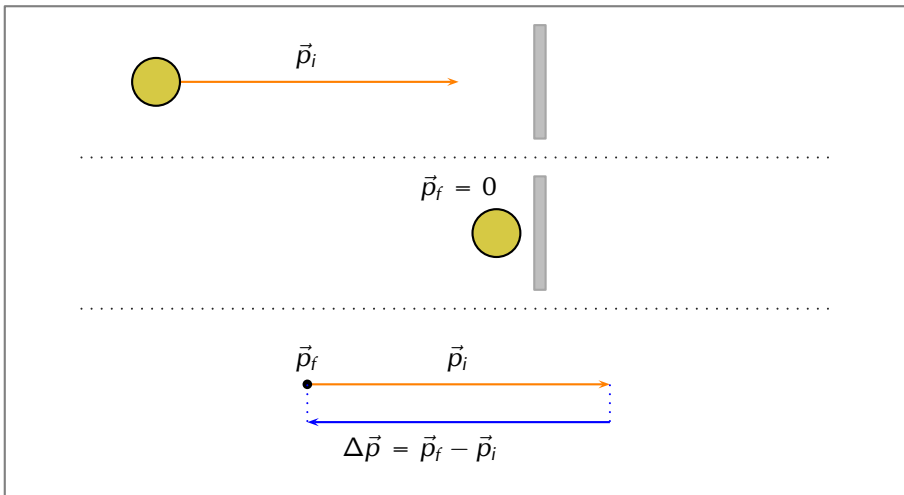
It will have momentum $\vec{p}_i = m\vec{v}_i$ to the right as shown in this picture:

The ball bounces off the wall. It will now be moving to the left, with the same mass, but a different velocity, $\vec{v}_f$ and therefore, a different momentum, $\vec{p}_f = m\vec{v}_f$, as shown in this picture:

We know that the final momentum vector must be the sum of the initial momentum vector and the change in momentum vector, $\Delta\vec{p} = m\Delta\vec{v}$. This means that, using tail-to-head vector addition, $\Delta\vec{p}$, must be the vector that starts at the head of $\vec{p}_i$ and ends on the head of $\vec{p}_f$ as shown in this picture:

We also know from algebraic addition of vectors that:

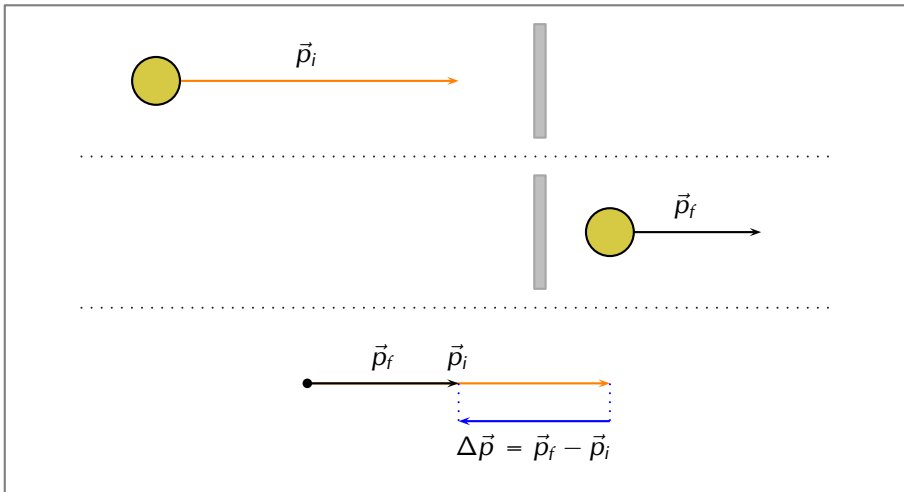
$$\begin{aligned} \vec{p}_f &= \vec{p}_i + \Delta\vec{p} \\ \vec{p}_f - \vec{p}_i &= \Delta\vec{p} \\ \Delta\vec{p} &= \vec{p}_f - \vec{p}_i \end{aligned}$$

If we put this all together we can show the sequence and the change in momentum in one diagram:

We have just shown the case for a rebounding object. There are a few other cases we can use to illustrate the basic features but they are all built up in the same way.

**Case 2: Object stops**

In some scenarios the object may come to a standstill (rest). An example of such a case is a tennis ball hitting the net. The net stops the ball but doesn't cause it to bounce back. At the instant before it falls to the ground its velocity is zero.

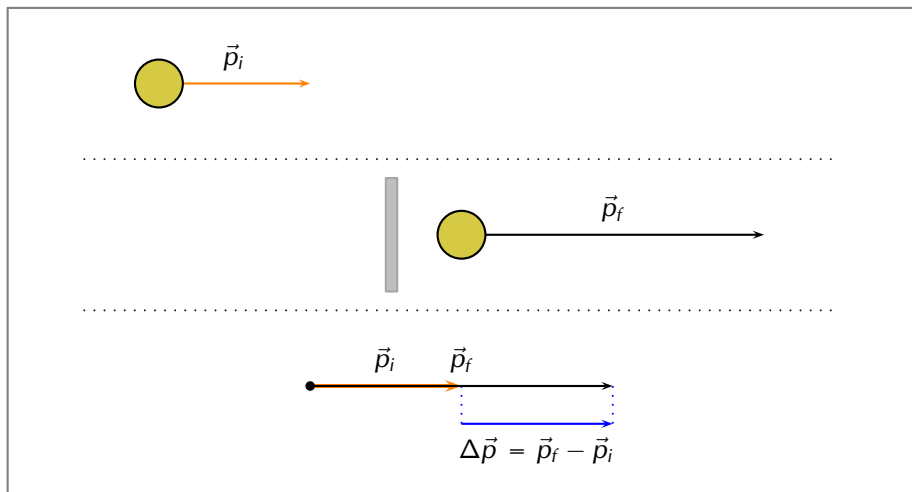
This scenario is described in this image:

#### Case 3: Object continues more slowly

In this case, the object continue in the same direction but more slowly. To give this some context, this could happen when a ball hits a glass window and goes through it or an object sliding on a frictionless surface encounters a small rough patch before carrying on along the frictionless surface.

**Important:** note that even though the momentum remains in the same direction the change in momentum is in the opposite direction because the magnitude of the final momentum is less than the magnitude of the initial momentum.

#### Case 4: Object gets a boost

In this case the object interacts with something that increases the velocity it has without changing its direction. For example, in squash the ball can bounce off a back wall

towards the front wall and a player can hit it with a racquet in the same direction, increasing its velocity.

If we analyse this scenario in the same way as the first 3 cases, it will look like this:

**Case 5: Vertical bounce**

**IMPORTANT!**

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For this explanation we are ignoring any effect of gravity. This isn't accurate but we will learn more about the role of gravity in this scenario in the next chapter.

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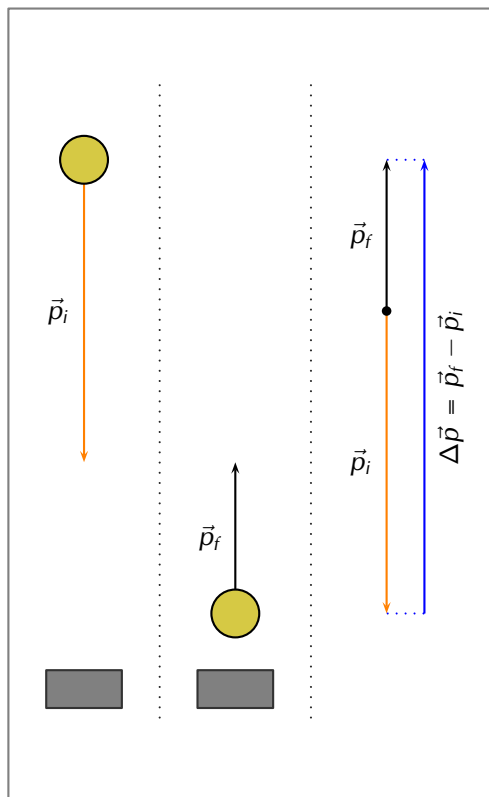
All of the examples that we've shown so far have been in the horizontal direction. That is just a coincidence, this approach applies for vertical or horizontal cases. In fact, it applies to any scenario where the initial and final vectors fall on the same line, any 1-dimensional (1D) problem. We will only deal with 1D scenarios in this chapter.

For example, a stationary basketball player bouncing a ball.

To illustrate the point, here is what the analysis would look like for a ball bouncing off the floor:

**Exercise 2 – 1:**

1. a) The fastest recorded delivery for a cricket ball is 161,3 km·hr$^{-1}$, bowled by Shoaib Akhtar of Pakistan during a match against England in the 2003 Cricket World Cup, held in South Africa. Calculate the ball's momentum if it has a mass of 160 g.
   b) The fastest tennis service by a man is 246,2 km·hr$^{-1}$ by Andy Roddick of the United States of America during a match in London in 2004. Calculate the ball's momentum if it has a mass of 58 g.
   c) The fastest server in the women's game is Venus Williams of the United States of America, who recorded a serve of 205 km·hr$^{-1}$ during a match in Switzerland in 1998. Calculate the ball's momentum if it has a mass of 58 g.
   d) If you had a choice of facing Shoaib, Andy or Venus and didn't want to get hurt, who would you choose based on the momentum of each ball?
2. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27HP

 **www.everythingscience.co.za**

In the previous section we considered a number of scenarios where the momentum of an object changed but we didn't look at the details of what caused the momentum to change. In each case it interacted with something which we know would have exerted a force on the object and we've learnt a lot about forces in Grade 11 so now we can tie the two together.

You have learnt about Newton's Laws of motion in Grade 11. We know that an object will continue in its state of motion unless acted on by a force so unless a force acts the momentum will not change.

In its most general form Newton's Second Law of motion is defined in terms of momentum which actually allows for the mass and the velocity to vary. We will not deal with the case of changing mass as well as changing velocity.

**DEFINITION:** *Newton's Second Law of Motion (N2)*

The net or resultant force acting on an object is equal to the rate of change of momentum.

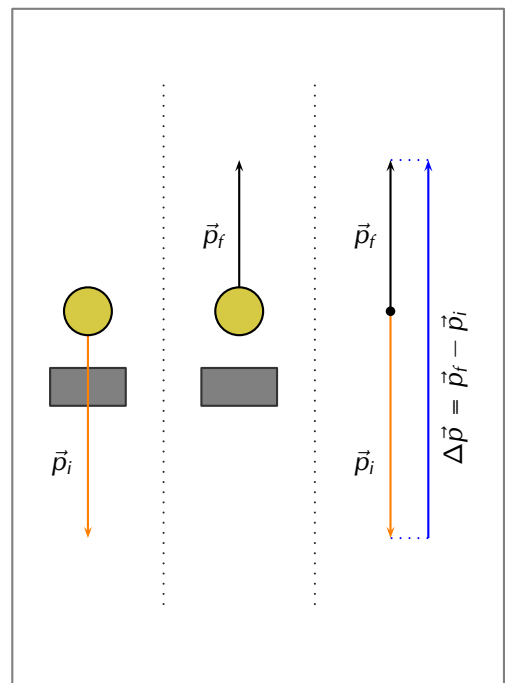
Mathematically, Newton's Second Law can be stated as: $\vec{F}_{net} = \frac{\Delta\vec{p}}{\Delta t}$

If a force is acting on an object whose mass is not changing, then Newton's Second Law describes the relationship between the motion of an object and the net force on the object through:

$$\vec{F}_{\text{net}} = m\vec{a}_{\text{net}}$$

We can therefore say that because a net force causes an object to change its motion, it also causes its momentum to change.

$$\begin{aligned}\vec{F}_{net} &= m\vec{a}_{\text{net}} \\ \vec{F}_{net} &= m\frac{\Delta\vec{v}}{\Delta t} \\ \vec{F}_{net} &= \frac{m\Delta\vec{v}}{\Delta t} \\ \vec{F}_{net} &= \frac{\Delta\vec{p}}{\Delta t}\end{aligned}$$

Let us apply this to the last case from the previous section, consider a tennis ball (mass = 0,1 kg) that is thrown and strikes the floor with a velocity of 5 m·s$^{-1}$ downwards and bounces back at a final velocity of 3 m·s$^{-1}$ upwards. As the ball approaches the floor it has an initial momentum $\vec{p}_i$. When it moves away from the floor it has a final momentum $\vec{p}_f$.

The bounce on the floor can be thought of as a collision taking place where the floor exerts a force on the tennis ball to change its momentum.

**Remember:** momentum and velocity are vectors so we have to choose a direction as positive. For this example we choose the initial direction of motion as positive, in other words, downwards is positive.

$$\begin{aligned}\vec{p}_i &= m\vec{v}_i \\ &= (0{,}1)\,(+5) \\ &= 0{,}5\ \text{kg·m·s}^{-1}\ \text{downwards}\end{aligned}$$

When the tennis ball bounces back it changes direction. The final velocity will thus have a negative value because it is in the negative direction. The momentum after the bounce can be calculated as follows:

$$\begin{aligned}\vec{p}_f &= m\vec{v}_f \\ &= (0{,}1)\,(-3) \\ &= -0{,}3 \\ &= 0{,}3\ \text{kg·m·s}^{-1}\ \text{upwards}\end{aligned}$$

Now let us look at what happens to the momentum of the tennis ball. The momentum changes during this bounce.

We keep our initial choice of downwards as positive. This means that the final momentum will have a negative number.

$$\begin{aligned}\Delta\vec{p} &= \vec{p}_f - \vec{p}_i \\ &= m\vec{v}_f - m\vec{v}_i \\ &= (-0{,}3) - (0{,}5) \\ &= -0{,}8 \\ &= 0{,}8\ \text{kg·m·s}^{-1}\ \text{upwards}\end{aligned}$$

You will notice that this number is bigger than the previous momenta calculated. This should be the case as the change has to cancel out the initial momentum and then still be as large as the final momentum over and above the initial momentum.

### Worked example 4: Change in Momentum

***QUESTION***

A tennis ball of mass 58 g strikes a wall perpendicularly with a velocity of 10 $\text{m·s}^{-1}$. It rebounds at a velocity of 8 $\text{m·s}^{-1}$. Calculate the change in the momentum of the tennis ball caused by the wall.

***SOLUTION***

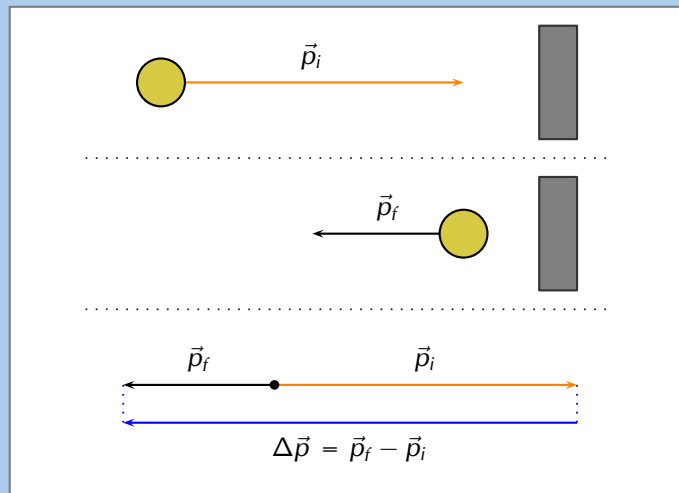
**Step 1: Identify the information given and what is asked**

The question explicitly gives a number of values which we identify and convert into SI units:

- the ball's mass (m = 58 g = 0,058 kg),
- the ball's initial velocity ($\vec{v}_i$ = 10 $\text{m·s}^{-1}$) towards the wall, and

- the ball's final velocity ($\vec{v}_f = 8\ \text{m·s}^{-1}$) away from the wall

We are asked to calculate the change in momentum of the ball,

$$\Delta\vec{p} = m\vec{v}_f - m\vec{v}_i$$

We have everything we need to find $\Delta\vec{p}$. Since the initial momentum is directed towards the wall and the final momentum is away from the wall, we can use the algebraic method of subtraction discussed in Vectors in Grade 10.

**Step 2: Choose a frame of reference**

Let us choose towards the wall as the positive direction.

**Step 3: Do the calculation**

$$\begin{aligned}\Delta\vec{p} &= m\vec{v}_f - m\vec{v}_i \\ &= (0{,}058)(-8) - (0{,}058)(+10) \\ &= (-0{,}46) - (0{,}58) \\ &= -1{,}04 \\ &= 1{,}04\ \text{kg·m·s}^{-1}\ \text{away from the wall}\end{aligned}$$

**Step 4: Quote the final answer**

The change in momentum is $1{,}04\ \text{kg·m·s}^{-1}$ away from the wall.

**Worked example 5: Change in momentum**

***QUESTION***

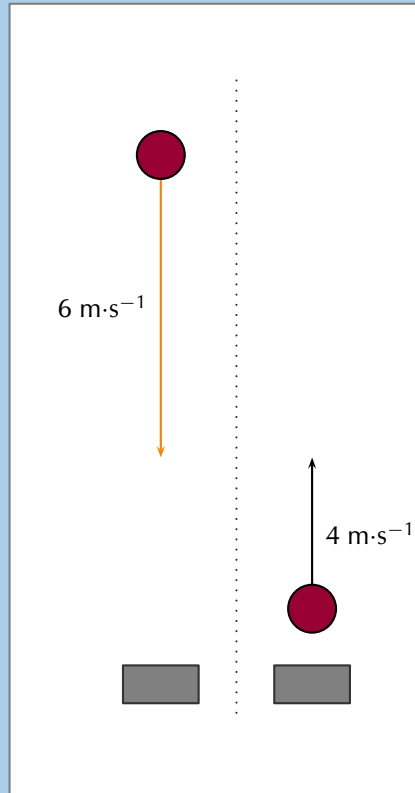
A rubber ball of mass 0,8 kg is dropped and strikes the floor with an initial velocity of $6\ \text{m·s}^{-1}$. It bounces back with a final velocity of $4\ \text{m·s}^{-1}$. Calculate the change in the momentum of the rubber ball caused by the floor.

**SOLUTION**

**Step 1: Identify the information given and what is asked**

The question explicitly gives a number of values which we identify and convert into SI units:

- the ball's mass ($m = 0{,}8$ kg),
- the ball's initial velocity ($\vec{v}_i = 6$ m·s$^{-1}$) downwards, and
- the ball's final velocity ($\vec{v}_f = 4$ m·s$^{-1}$) upwards

We are asked to calculate the change in momentum of the ball,

$$\Delta \vec{p} = m\vec{v}_f - m\vec{v}_i$$

**Step 2: Do the calculation**

Let us choose down as the positive direction.

$$\begin{aligned}\Delta \vec{p} &= m\vec{v}_f - m\vec{v}_i \\ &= (0{,}8)(-4) - (0{,}8)(+6) \\ &= (-3{,}2) - (4{,}8) \\ &= -8 \\ &= 8{,}0 \text{ kg·m·s}^{-1} \text{ upwards}\end{aligned}$$

**Step 3: Quote the final answer**

The change in momentum is 8,0 kg·m·s$^{-1}$ upwards.

**Worked example 6: Change in momentum**

**QUESTION**

A regulation squash ball weighs 24 g. In a squash match a ball bounces off the back wall in the direction of the front wall at 1 m·s$^{-1}$ before a player hits it with a racquet. After being struck towards the front wall the ball is moving at 20 m·s$^{-1}$. What is the change in momentum?

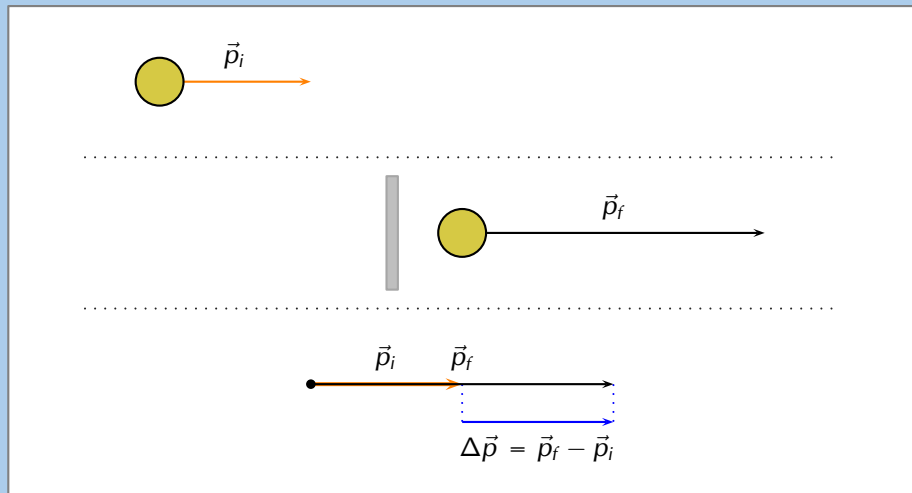
**SOLUTION**

**Step 1: Identify the information given and what is asked**

The question explicitly gives a number of values which we identify and convert into SI

units:

- the ball's mass ($m = 24$ g$=$0,024 kg),
- the ball's initial velocity ($\vec{v}_i = 1$ m·s$^{-1}$) towards the front wall, and
- the ball's final velocity ($\vec{v}_f = 20$ m·s$^{-1}$) towards the front wall

We are asked to calculate the change in momentum of the ball,

$$\Delta\vec{p} = m\vec{v}_f - m\vec{v}_i$$

We have everything we need to find $\Delta\vec{p}$.

**Step 2: Choose a frame of reference**
Let us choose towards the front wall as the positive direction.

**Step 3: Do the calculation**

$$\begin{aligned}\Delta\vec{p} &= m\vec{v}_f - m\vec{v}_i \\ &= (0{,}024)(20) - (0{,}024)(+1) \\ &= (0{,}48) - (0{,}024) \\ &= 0{,}456 \\ &= 0{,}46 \text{ kg·m·s}^{-1} \text{ towards the front wall}\end{aligned}$$

**Step 4: Quote the final answer**
The change in momentum is 0,46 kg·m·s$^{-1}$ towards the front wall.

**Exercise 2 – 2:**

1. Which expression accurately describes the change of momentum of an object?
   a) $\frac{\vec{F}}{m}$
   b) $\frac{\vec{F}}{\Delta t}$
   c) $\vec{F} \cdot m$
   d) $\vec{F} \cdot \Delta t$
2. A child drops a ball of mass 100 g. The ball strikes the ground with a velocity of 5 m·s$^{-1}$ and rebounds with a velocity of 4 m·s$^{-1}$. Calculate the change of momentum of the ball.
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27HQ 2. 27HR

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## 2.4 Conservation of momentum ESCJC

In this section we are going to look at momentum when two objects interact with each other and, specifically, treat both objects as one system. To do this properly we first need to define what we mean we talk about a system, then we need to look at what happens to momentum overall and we will explore the applications of momentum in these interactions.

### Systems ESCJD

**DEFINITION:** *System*

A system is a physical configuration of particles and or objects that we study.

For example, earlier we looked at what happens when a ball bounces off a wall. The system that we were studying was just the wall and the ball. The wall must be connected to the Earth and something must have thrown or hit the ball but we ignore those. A system is a subset of the physical world that we are studying. The system exists in some larger environment.

In the problems that we are solving we actually treat our system as being isolated from the environment. That means that we can completely ignore the environment. In reality, the environment can affect the system but we ignore that for isolated systems. We try to choose isolated systems when it makes sense to ignore the surrounding

environment.

**DEFINITION:** *Isolated system*

An isolated system is a physical configuration of particles and or objects that we study that doesn't exchange any matter with its surroundings and is not subject to any force whose source is external to the system.

An external force is a force acting on the pieces of the system that we are studying that is not caused by a component of the system.

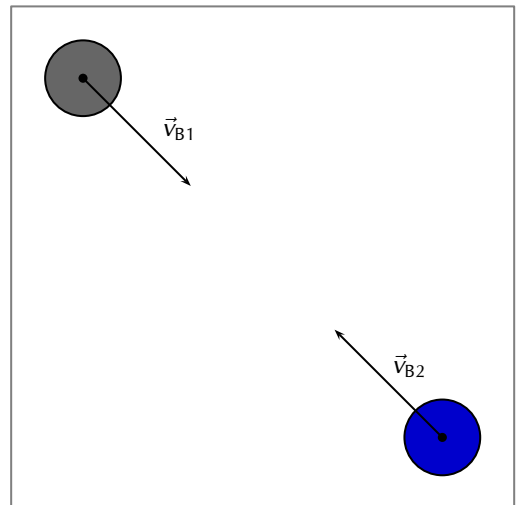
It is a choice we make to treat objects as an isolated system but we can only do this if we think it really make sense, if the results we are going to get will still be reasonable. In reality, no system is competely isolated except for the whole universe (we think). When we look at a ball hitting a wall it makes sense to ignore the force of gravity. The effect isn't exactly zero but it will be so small that it will not make any real difference to our results.

## Conservation of momentum ESCJF

There is a very useful property of isolated systems, total momentum is conserved. Lets use a practical example to show why this is the case, let us consider two billiard balls moving towards each other. Here is a sketch alongside (not to scale). When they come into contact, ball 1 exerts a contact force on the ball 2, $\vec{F}_{B1}$, and the ball 2 exerts a force on ball 1, $\vec{F}_{B2}$. We also know that the force will result in a change in momentum:

$$\vec{F}_{net} = \frac{\Delta \vec{p}}{\Delta t}$$

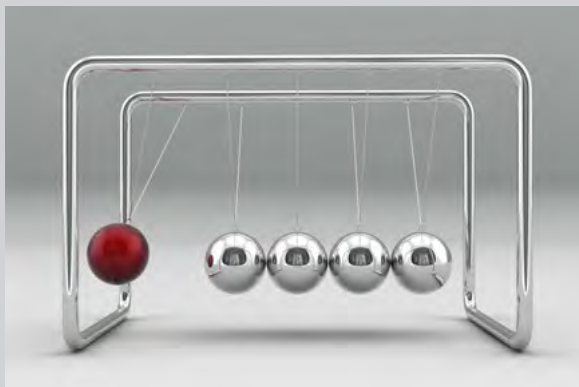
We also know from Newton's third law that:

$$\begin{aligned}
\vec{F}_{B1} &= -\vec{F}_{B2} \\
\frac{\Delta \vec{p}_{B1}}{\Delta t} &= -\frac{\Delta \vec{p}_{B2}}{\Delta t} \\
\Delta \vec{p}_{B1} &= -\Delta \vec{p}_{B2} \\
\Delta \vec{p}_{B1} + \Delta \vec{p}_{B2} &= 0
\end{aligned}$$

This says that if you add up all the changes in momentum for an isolated system the net result will be zero. If we add up all the momenta in the system the total momentum won't change because the net change is zero.

**Important:** note that this is because the forces are internal forces and Newton's third law applies. An external force would not necessarily allow momentum to be conserved. In the absence of an external force acting on a system, momentum is conserved.

**Activity: Newton's cradle demonstration**

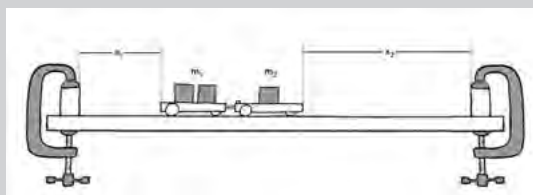
**Momentum conservation:**

A Newton's cradle demonstrates a series of collisions in which momentum is conserved.

**Informal experiment: Conservation of momentum**

**Aim:**

To investigate the changes in momentum when two bodies are separated by an explosive force.

**Apparatus:**

- two spring-loaded trolleys
- stopwatch
- meter-stick
- two barriers

**Method:**

- Clamp the barriers one metre apart onto a flat surface.
- Find the mass of each trolley and place a known mass on one of the trolleys.
- Place the two trolleys between the barriers end to end so that the spring on the one trolley is in contact with the flat surface of the other trolley
- Release the spring by hitting the release knob and observe how the trolleys push each other apart.
- Repeat the explosions with the trolleys at a different position until they strike the barriers simultaneously. Each trolley now has the same time of travel t.
- Measure the distances $x_1$ and $x_2$. These can be taken as measures of the respective velocities.

- Repeat the experiment for a different combination of masses.

**Results:**

Record your results in a table, using the following headings for each trolley. Total mass in kg, distance travelled in m, momentum in kg·m·s$^{-1}$. What is the relationship between the total momentum after the explosion and the total momentum before the explosion?

**DEFINITION:** *Conservation of Momentum*

The total momentum of an isolated system is constant.

The total momentum of a system is calculated by the vector sum of the momenta of all the objects or particles in the system. For a system with $n$ objects the total momentum is:

$$\vec{p}_T = \vec{p}_1 + \vec{p}_2 + \ldots + \vec{p}_n$$

**Worked example 7: Calculating the total momentum of a system**

***QUESTION***

Two billiard balls roll towards each other. They each have a mass of 0,3 kg. Ball 1 is moving at $\vec{v}_1 = 1$ m·s$^{-1}$ to the right, while ball 2 is moving at $\vec{v}_2 = 0{,}8$ m·s$^{-1}$ to the left. Calculate the total momentum of the system.

***SOLUTION***

**Step 1: Identify what information is given and what is asked for**

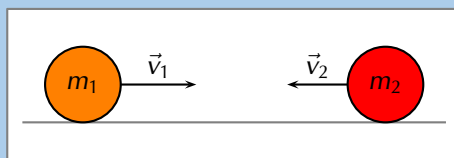
The question explicitly gives

- the mass of each ball,
- the velocity of ball 1, $\vec{v}_1$, and
- the velocity of ball 2, $\vec{v}_2$,

all in the correct units.

We are asked to calculate the **total momentum of the system**. In this example our system consists of two balls. To find the total momentum we must determine the momentum of each ball and add them.

$$\vec{p}_T = \vec{p}_1 + \vec{p}_2$$

Since ball 1 is moving to the right, its momentum is in this direction, while the second ball's momentum is directed towards the left.

Thus, we are required to find the sum of two vectors acting along the same straight line.

**Step 2: Choose a frame of reference**

Let us choose moving to the right as the positive direction.

**Step 3: Calculate the momentum**

The total momentum of the system is then the sum of the two momenta taking the directions of the velocities into account. Ball 1 is travelling at 1 m·s$^{-1}$ to the right or +1 m·s$^{-1}$. Ball 2 is travelling at 0,8 m·s$^{-1}$ to the left or −0,8 m·s$^{-1}$. Thus,

$$\begin{aligned} \vec{p}_T &= m_1\vec{v}_1 + m_2\vec{v}_2 \\ &= (0{,}3)(+1) + (0{,}3)(-0{,}8) \\ &= (+0{,}3) + (-0{,}24) \\ &= +0{,}06 \\ &= 0{,}06 \text{ m·s}^{-1} \text{ to the right} \end{aligned}$$

In the last step the direction was added in words. Since the result in the second last line is positive, the total momentum of the system is in the positive direction (i.e. to the right).

**Exercise 2 – 3:**

1. Two golf balls roll towards each other. They each have a mass of 100 g. Ball 1 is moving at $\vec{v}_1 = 2{,}4$ m·s$^{-1}$ to the right, while ball 2 is moving at $\vec{v}_2 = 3$ m·s$^{-1}$ to the left. Calculate the total momentum of the system.
2. Two motorcycles are involved in a head on collision. Motorcycle A has a mass of 200 kg and was travelling at 120 km·hr$^{-1}$ south. Motor cycle B has a mass of 250 kg and was travelling north at 100 km·hr$^{-1}$. A and B are about to collide. Calculate the momentum of the system before the collision takes place.
3. A 700 kg truck is travelling north at a velocity of 40 km·hr$^{-1}$ when it is approached by a 500 kg car travelling south at a velocity of 100 km·hr$^{-1}$. Calculate the total momentum of the system.
4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27HS 2. 27HT 3. 27HV

We have shown that the net change in momentum is zero for an isolated system. The momenta of the **individual objects can change** but the total momentum of the **system remains constant**.

This means that it makes sense to define the total momentum at the begining of the problem as the initial total momentum, $\vec{p}_{Ti}$, and the final total momentum $\vec{p}_{Tf}$. Momentum conservation implies that, no matter what happens inside an isolated system:

$$\vec{p}_{Ti} = \vec{p}_{Tf}$$

This means that in an isolated system the total momentum before a **collision** or **explosion** is equal to the total momentum after the collision or explosion.

Consider a simple collision of two billiard balls. The balls are rolling on a frictionless, horizontal surface and the system is isolated. We can apply conservation of momentum. The first ball has a mass $m_1$ and an initial velocity $\vec{v}_{i1}$. The second ball has a mass $m_2$ and moves first ball with an initial velocity $\vec{v}_{i2}$. This situation is shown in Figure 2.1.

Figure 2.1: Before the collision.

The total momentum of the system before the collision, $\vec{p}_{Ti}$ is: $\vec{p}_{Ti} = m_1\vec{v}_{i1} + m_2\vec{v}_{i2}$

After the two balls collide and move away they each have a different momentum. If the first ball has a final velocity of $\vec{v}_{f1}$ and the second ball has a final velocity of $\vec{v}_{f2}$ then we have the situation shown in 2.2.

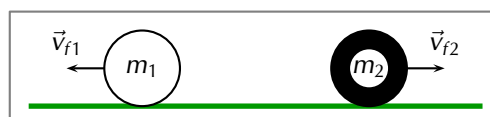



Figure 2.2: After the collision.

The total momentum of the system after the collision, $\vec{p}_{Tf}$ is: $\vec{p}_{Tf} = m_1\vec{v}_{f1} + m_2\vec{v}_{f2}$

This system of two balls is isolated since there are no external forces acting on the balls. Therefore, by the principle of conservation of linear momentum, the total momentum before the collision is equal to the total momentum after the collision. This gives the equation for the conservation of momentum in a collision of two objects,

| $\vec{p}_i = \vec{p}_f$ | $m_1\vec{v}_{i1} + m_2\vec{v}_{i2} = m_1\vec{v}_{f1} + m_2\vec{v}_{f2}$ |
|---|---|
| | |
| $m_1$ | : mass of object 1 (kg) |
| $m_2$ | : mass of object 2 (kg) |
| $\vec{v}_{i1}$ | : initial velocity of object 1 (m·s$^{-1}$ + direction) |
| $\vec{v}_{i2}$ | : initial velocity of object 2 (m·s$^{-1}$ - direction) |
| $\vec{v}_{f1}$ | : final velocity of object 1 (m·s$^{-1}$ - direction) |
| $\vec{v}_{f2}$ | : final velocity of object 2 (m·s$^{-1}$ + direction) |

This equation is always true - momentum is always conserved in collisions.

**Worked example 8: Conservation of momentum**

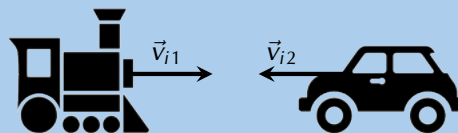
***QUESTION***

A toy car of mass 1 kg moves westwards with a speed of 2 m·s$^{-1}$. It collides head-on with a toy train. The train has a mass of 1,5 kg and is moving at a speed of 1,5 m·s$^{-1}$ eastwards. If the car rebounds at 2,05 m·s$^{-1}$, calculate the final velocity of the train.

***SOLUTION***

**Step 1: Analyse what you are given and draw a sketch**

The question explicitly gives a number of values which we identify and convert into SI units if necessary:

- the train's mass ($m_1 = 1,50$ kg),
- the train's initial velocity ($\vec{v}_{1i} = 1,5$ m·s$^{-1}$ eastward),
- the car's mass ($m_2 = 1,00$ kg),
- the car's initial velocity ($\vec{v}_{2i} = 2,00$ m·s$^{-1}$ westward), and
- the car's final velocity ($\vec{v}_{2f} = 2,05$ m·s$^{-1}$ eastward).

We are asked to find the final velocity of the train.

**Step 2: Choose a frame of reference**

We will choose to the East as positive.

**Step 3: Apply the Law of Conservation of momentum**

$$\begin{aligned}
\vec{p}_{Ti} &= \vec{p}_{Tf} \\
m_1\vec{v}_{i1} + m_2\vec{v}_{i2} &= m_1\vec{v}_{f1} + m_2\vec{v}_{f2} \\
(1,5)(+1,5) + (2)(-2) &= (1,5)\left(\vec{v}_{f1}\right) + (2)(2,05) \\
2,25 - 4 - 4,1 &= (1,5)\vec{v}_{f1} \\
5,85 &= (1,5)\vec{v}_{f1} \\
\vec{v}_{f1} &= 3,9 \text{ m} \cdot \text{s}^{-1} \text{ eastwards}
\end{aligned}$$

**Worked example 9: Conservation of momentum**

***QUESTION***

A jet flies at a speed of 275 $\text{m}\cdot\text{s}^{-1}$. The pilot fires a missile forward off a mounting at a speed of 700 $\text{m}\cdot\text{s}^{-1}$ relative to the ground. The respective masses of the jet and the missile are 5000 kg and 50 kg. Treating the system as an isolated system, calculate the new speed of the jet immediately after the missile had been fired.

***SOLUTION***

**Step 1: Analyse what you are given and draw a sketch**

The question explicitly gives a number of values which we identify and convert into SI units if necessary:

- the mass of the jet ($m_1 = 5000$ kg)
- the mass of the rocket ($m_2 = 50$ kg)
- the initial velocity of the jet and rocket ($\vec{v}_{i1} = \vec{v}_{i2} = 275\ \text{m}\cdot\text{s}^{-1}$ to the left)
- the final velocity of the rocket ($\vec{v}_{f2} = 700\ \text{m}\cdot\text{s}^{-1}$ to the left)

We need to find the final speed of the jet and we can use momentum conservation because we can treat it as an isolated system.

We choose the original direction that the jet was flying in as the positive direction, to the left.

After the missile is launched we need to take both into account:

Figure 2.3: System is jet and missile

**Step 2: Apply the Law of Conservation of momentum**

The jet and missile are connected initially and move at the same velocity. We will therefore combine their masses and change the momentum equation as follows:

$$\begin{aligned}
\vec{p}_i &= \vec{p}_f \\
(m_1 + m_2)\,\vec{v}_i &= m_1\vec{v}_{f1} + m_2\vec{v}_{f2} \\
(5000 + 50)\,(275\ ) &= (5000)\left(\vec{v}_{f1}\right) + (50)\,(700\ ) \\
1\ 388\ 750 - 35\ 000 &= (5000)\left(\vec{v}_{f1}\right) \\
\vec{v}_{f1} &= 270{,}75\ \text{m·s}^{-1}\ \text{in the original direction}
\end{aligned}$$

**Step 3: Quote the final answer**

The speed of the jet is the magnitude of the final velocity, 270,75 m·s$^{-1}$.

**Worked example 10: Conservation of momentum**

***QUESTION***

A bullet of mass 50 g travelling horizontally to the right at 500 m·s$^{-1}$ strikes a stationary wooden block of mass 2 kg resting on a smooth horizontal surface. The bullet goes through the block and comes out on the other side at 200 m·s$^{-1}$. Calculate the speed of the block after the bullet has come out the other side.

***SOLUTION***

**Step 1: Analyse what you are given and draw a sketch**

The question explicitly gives a number of values which we identify and convert into SI units if necessary:

- the mass of the bullet ($m_1 = 50\ \text{g} = 0{,}50\ \text{kg}$)
- the mass of the block ($m_2 = 2{,}00\ \text{kg}$)
- the initial velocity of the bullet ($\vec{v}_{i1} = 500\ \text{m·s}^{-1}$ to the right)
- the final velocity of the bullet ($\vec{v}_{f1} = 200\ \text{m·s}^{-1}$ to the right)

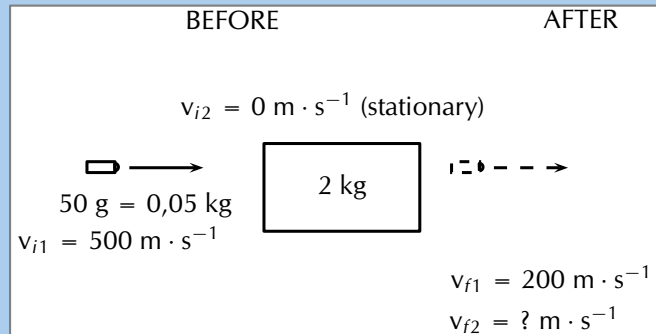
We need to find the velocity of the wood block. We choose the direction in which the bullet was travelling to be the positive direction, to the right.

BEFORE AFTER

$v_{i2} = 0\ m \cdot s^{-1}$ (stationary)

2 kg

50 g = 0,05 kg
$v_{i1} = 500\ m \cdot s^{-1}$

$v_{f1} = 200\ m \cdot s^{-1}$
$v_{f2} = ?\ m \cdot s^{-1}$

**Step 2: Apply the Law of Conservation of momentum**

$$\begin{aligned} \vec{p}_i &= p_f \\ m_1\vec{v}_{i1} + m_2\vec{v}_{i2} &= m_1\vec{v}_{f1} + m_2\vec{v}_{f2} \\ (0{,}05)(+500) + (2)(0) &= (0{,}05)(+200) + (2)\left(\vec{v}_{f2}\right) \\ 25 + 0 - 10 &= 2\ \vec{v}_{f2} \\ \vec{v}_{f2} &= 7{,}5 m{\cdot}s^{-1} \text{ in the same direction as the bullet} \end{aligned}$$

**Step 3: Apply the Law of Conservation of momentum**
The block is travelling at $7{,}5\ m{\cdot}s^{-1}$.

We have been applying conservation of momentum to collisions and explosion which is valid but there are actually two different types of collisions and they have different properties.

Two types of collisions are of interest:

- elastic collisions
- inelastic collisions

In both types of collision, total momentum is *always* conserved. Kinetic energy is conserved for elastic collisions, but not for inelastic collisions.

Initially in a collision the objects have kinetic energy. In some collisions that energy is transformed through processes like deformation. In a car crash the car gets all mangled which requires the permanent transfer of energy.

**DEFINITION:** *Elastic Collisions*

An elastic collision is a collision where total momentum and total kinetic energy are both conserved.

This means that in an elastic collision the total momentum *and* the total kinetic energy before the collision is the same as after the collision. For these kinds of collisions, the kinetic energy is not tranformed permanently through work or deformation of the objects. During the collision the energy is going to be transferred (for example as a ball compresses) but will be recovered during the elastic response of the system (for example the ball then expanding again).

**Before the collision**

2.4 shows two balls rolling toward each other, about to collide:

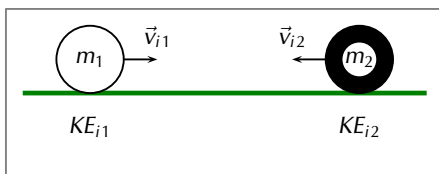



Figure 2.4: Two balls before they collide.

We have calculated the total initial momentum previously, now we calculate the total kinetic energy of the system in the same way. Ball 1 has a kinetic energy which we call $KE_{i1}$ and ball 2 has a kinetic energy which we call $\text{KE}_{i2}$, the total kinetic energy before the collision is: $KE_{Ti} = KE_{i1} + KE_{i2}$

**After the collision**

2.5 shows two balls after they have collided:

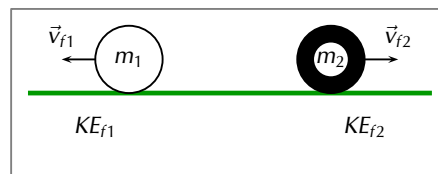



Figure 2.5: Two balls after they collide.

Ball 1 now has a kinetic energy which we call $KE_{f1}$ and ball 2 now has a kinetic energy which we call $\text{KE}_{f2}$, it means that the total kinetic energy after the collision is: $KE_{Tf} = KE_{f1} + KE_{f2}$

Since this is an *elastic* collision, the total momentum before the collision equals the total momentum after the collision **and** the total kinetic energy before the collision equals the total kinetic energy after the collision. Therefore:

$$\vec{p}_{Ti} = \vec{p}_{Tf}$$
$$\vec{p}_{i1} + \vec{p}_{i2} = \vec{p}_{f1} + \vec{p}_{f2}$$

and

$$\text{KE}_{Ti} = \text{KE}_{Tf}$$
$$\text{KE}_{i1} + \text{KE}_{i2} = \text{KE}_{f1} + \text{KE}_{f2}$$

**Worked example 11: An elastic collision**

***QUESTION***

Consider a collision between two pool balls. Ball 1 is at rest and ball 2 is moving towards it with a speed of 2 m·s$^{-1}$. The mass of each ball is 0,3 kg. After the balls collide *elastically*, ball 2 comes to an immediate stop and ball 1 moves off. What is the final velocity of ball 1?

***SOLUTION***

**Step 1: Choose a frame of reference**

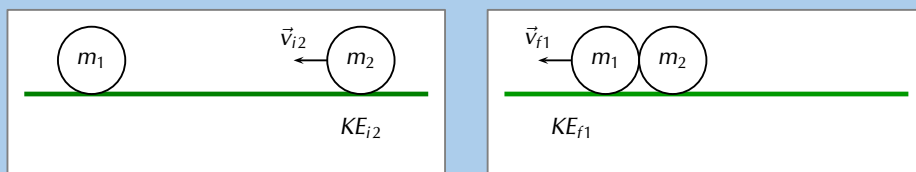
Choose to the right as positive and we assume that ball 2 is moving towards the left approaching ball 1.

**Step 2: Determine what is given and what is needed**

- Mass of ball 1, $m_1 = 0,3$ kg.
- Mass of ball 2, $m_2 = 0,3$ kg.
- Initial velocity of ball 1, $\vec{v}_{i1} = 0$ m·s$^{-1}$.
- Initial velocity of ball 2, $\vec{v}_{i2} = 2$ m·s$^{-1}$ to the left.
- Final velocity of ball 2, $\vec{v}_{f2} = 0$ m·s$^{-1}$.
- The collision is elastic.

All quantities are in SI units. We need to find the final velocity of ball 1, $v_{f1}$. Since the collision is elastic, we know that

- momentum is conserved, $m_1\vec{v}_{i1} + m_2\vec{v}_{i2} = m_1\vec{v}_{f1} + m_2\vec{v}_{f2}$
- energy is conserved, $\frac{1}{2}\left(m_1 v_{i1}^2 + m_2 v_{i2}^2\right) = \frac{1}{2}\left(m_1 v_{f1}^2 + m_2 v_{f2}^2\right)$

**Step 3: Draw a rough sketch of the situation**

**Step 4: Solve the problem**

Momentum is conserved in all collisions so it makes sense to begin with momentum. Therefore:

$$\begin{aligned}
\vec{p}_{Ti} &= \vec{p}_{Tf} \\
m_1\vec{v}_{i1} + m_2\vec{v}_{i2} &= m_1\vec{v}_{f1} + m_2\vec{v}_{f2} \\
(0,3)(0) + (0,3)(-2) &= (0,3)\,\vec{v}_{f1} + 0 \\
\vec{v}_{f1} &= -2{,}00 \text{ m·s}^{-1}
\end{aligned}$$

**Step 5: Quote your final answer**

The final velocity of ball 1 is 2 m·s$^{-1}$ to the left.

**Worked example 12: Another elastic collision**

***QUESTION***

Consider 2 marbles. Marble 1 has mass 50 g and marble 2 has mass 100 g. Edward rolls marble 2 along the ground towards marble 1 in the positive x-direction. Marble 1 is initially at rest and marble 2 has a velocity of 3 m·s$^{-1}$ in the positive x-direction. After they collide *elastically*, both marbles are moving. What is the final velocity of each marble?

***SOLUTION***

**Step 1: Decide how to approach the problem**

We are given:

- mass of marble 1, $m_1 = 50$ g
- mass of marble 2, $m_2 = 100$ g
- initial velocity of marble 1, $\vec{v}_{i1} = 0$ m·s$^{-1}$
- initial velocity of marble 2, $\vec{v}_{i2} = 3$ m·s$^{-1}$ to the right
- the collision is elastic

The masses need to be converted to SI units.

$$m_1 = 0,05\text{kg}$$
$$m_2 = 0,1\text{kg}$$

We are required to determine the final velocities:

- final velocity of marble 1, $\vec{v}_{f1}$
- final velocity of marble 2, $\vec{v}_{f2}$

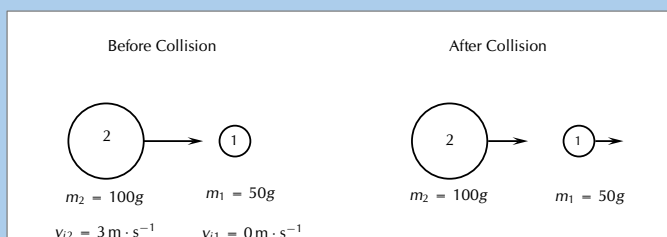
Since the collision is elastic, we know that

- momentum is conserved, $\vec{p}_{Ti} = \vec{p}_{Tf}$.
- energy is conserved, $KE_{Ti} = KE_{Tf}$.

We have two equations and two unknowns ($\vec{v}_1$, $\vec{v}_2$) so it is a simple case of solving a set of simultaneous equations.

**Step 2: Choose a frame of reference**

Choose to the right as positive.

**Step 3: Draw a rough sketch of the situation**

**Step 4: Solve the problem**

Momentum is conserved. Therefore:

$$\begin{aligned}
\vec{p}_i &= \vec{p}_f \\
\vec{p}_{i1} + \vec{p}_{i2} &= \vec{p}_{f1} + \vec{p}_{f2} \\
m_1\vec{v}_{i1} + m_2\vec{v}_{i2} &= m_1\vec{v}_{f1} + m_2\vec{v}_{f2} \\
m_2\vec{v}_{i2} &= m_1\vec{v}_{f1} + m_2\vec{v}_{f2} \\
m_1\vec{v}_{f1} &= m_2\vec{v}_{i2} - m_2\vec{v}_{f2} \\
\vec{v}_{f1} &= \frac{m_2}{m_1}(\vec{v}_{i2} - \vec{v}_{f2})
\end{aligned}$$

Energy is also conserved. Therefore:

$$\begin{aligned}
KE_i &= KE_f \\
KE_{i1} + KE_{i2} &= KE_{f1} + KE_{f2} \\
\frac{1}{2}m_1 v_{i1}^2 + \frac{1}{2}m_2 v_{i2}^2 &= \frac{1}{2}m_1 v_{f1}^2 + \frac{1}{2}m_2 v_{f2}^2 \\
\frac{1}{2}m_2 v_{i2}^2 &= \frac{1}{2}m_1 v_{f1}^2 + \frac{1}{2}m_2 v_{f2}^2 \\
m_2 v_{i2}^2 &= m_1 v_{f1}^2 + m_2 v_{f2}^2
\end{aligned}$$

Substitute the expression we derived from conservation of momentum into the expression derived from conservation of kinetic energy and solve for $v_{f2}$.

$$\begin{aligned}
m_2 v_{i2}^2 &= m_1 v_{f1}^2 + m_2 v_{f2}^2 \\
&= m_1\left(\frac{m_2}{m_1}(v_{i2} - v_{f2})\right)^2 + m_2 v_{f2}^2 \\
&= m_1\frac{m_2^2}{m_1^2}(v_{i2} - v_{f2})^2 + m_2 v_{f2}^2 \\
&= \frac{m_2^2}{m_1}(v_{i2} - v_{f2})^2 + m_2 v_{f2}^2 \\
v_{i2}^2 &= \frac{m_2}{m_1}(v_{i2} - v_{f2})^2 + v_{f2}^2 \\
&= \frac{m_2}{m_1}\left(v_{i2}^2 - 2\cdot v_{i2}\cdot v_{f2} + v_{f2}^2\right) + v_{f2}^2 \\
0 &= \left(\frac{m_2}{m_1} - 1\right)v_{i2}^2 - 2\frac{m_2}{m_1}v_{i2}\cdot v_{f2} + \left(\frac{m_2}{m_1} + 1\right)v_{f2}^2 \\
&= \left(\frac{0.1}{0.05} - 1\right)(3)^2 - 2\frac{0.1}{0.05}(3)\cdot v_{f2} + \left(\frac{0.1}{0.05} + 1\right)v_{f2}^2 \\
&= (2-1)(3)^2 - 2\cdot 2(3)\cdot v_{f2} + (2+1)v_{f2}^2 \\
&= 9 - 12v_{f2} + 3v_{f2}^2 \\
&= 3 - 4v_{f2} + v_{f2}^2 \\
&= (v_{f2} - 3)(v_{f2} - 1)
\end{aligned}$$

Therefore $v_{f2} = 1$ or $v_{f2} = 3$

Substituting back into the expression from conservation of momentum, we get:

$$\begin{aligned} v_{f1} &= \frac{m_2}{m_1}(v_{i2} - v_{f2}) \\ &= \frac{0.1}{0.05}(3 - 3) \\ &= 0 \end{aligned}$$

or

$$\begin{aligned} v_{f1} &= \frac{m_2}{m_1}(v_{i2} - v_{f2}) \\ &= \frac{0.1}{0.05}(3 - 1) \\ &= 4 \text{ m·s}^{-1} \end{aligned}$$

But according to the question, marble 1 is moving after the collision, therefore marble 1 moves to the right at 4 m·s$^{-1}$.

Therefore marble 2 moves with a velocity of 1 m·s$^{-1}$ to the right.

**Worked example 13: Colliding billiard balls**

***QUESTION***

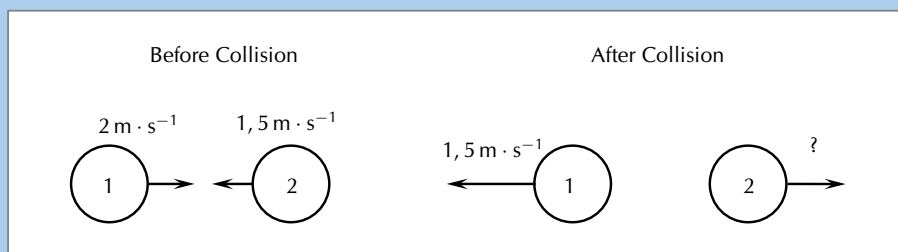
Two billiard balls each with a mass of 150 g collide head-on in an elastic collision. Ball 1 was travelling at a speed of 2 m·s$^{-1}$ and ball 2 at a speed of 1,5 m·s$^{-1}$. After the collision, ball 1 travels away from ball 2 at a velocity of 1,5 m·s$^{-1}$.

1. Calculate the velocity of ball 2 after the collision.
2. Prove that the collision was elastic. Show calculations.

***SOLUTION***

**Step 1: Choose a frame of reference**

Choose to the right as positive.

**Step 2: Draw a rough sketch of the situation**

**Step 3: Decide how to approach the problem**

Since momentum is conserved in all kinds of collisions, we can use conservation of momentum to solve for the velocity of ball 2 after the collision.

**Step 4: Solve problem**

$$
\begin{aligned}
\vec{p}_{Ti} &= \vec{p}_{Tf} \\
m_1\vec{v}_{i1} + m_2\vec{v}_{i2} &= m_1\vec{v}_{f1} + m_2\vec{v}_{f2} \\
\left(\frac{150}{1000}\right)(2) + \left(\frac{150}{1000}\right)(-1,5) &= \left(\frac{150}{1000}\right)(-1,5) + \left(\frac{150}{1000}\right)(\vec{v}_{f2}) \\
0,3 - 0,225 &= -0,225 + 0,15\vec{v}_{f2} \\
\vec{v}_{f2} &= 3 \text{ m·s}^{-1}
\end{aligned}
$$

So after the collision, ball 2 moves with a velocity of 3 $\text{m·s}^{-1}$ to the right.

**Step 5: Elastic collisions**

The fact that characterises an elastic collision is that the total kinetic energy of the particles before the collision is the same as the total kinetic energy of the particles after the collision. This means that if we can show that the initial kinetic energy is equal to the final kinetic energy, we have shown that the collision is elastic.

**Step 6: Calculating the initial total kinetic energy**

$$
\begin{aligned}
EK_{before} &= \frac{1}{2}m_1v_{i1}^2 + \frac{1}{2}m_2v_{i2}^2 \\
&= \left(\frac{1}{2}\right)(0,15)(2)^2 + \left(\frac{1}{2}\right)(0,15)(-1,5)^2 \\
&= 0.469....\text{J}
\end{aligned}
$$

**Step 7: Calculating the final total kinetic energy**

$$
\begin{aligned}
EK_{after} &= \frac{1}{2}m_1v_{f1}^2 + \frac{1}{2}m_2v_{f2}^2 \\
&= \left(\frac{1}{2}\right)(0,15)(-1,5)^2 + \left(\frac{1}{2}\right)(0,15)(2)^2 \\
&= 0.469....\text{J}
\end{aligned}
$$

So $EK_{Ti} = EK_{Tf}$ and hence the collision is elastic.

## Inelastic collisions ESCJJ

**DEFINITION:** *Inelastic Collisions*

An inelastic collision is a collision in which **total momentum** is conserved but **total kinetic energy** is *not* conserved. The kinetic energy is *transformed* from or into other kinds of energy.

So the total momentum before an inelastic collisions is the same as after the collision. But the total *kinetic* energy before and after the inelastic collision is *different*. Of course this does not mean that total energy has not been conserved, rather the energy has been *transformed* into another type of energy.

As a rule of thumb, inelastic collisions happen when the colliding objects are distorted in some way. Usually they change their shape. The modification of the shape of an object requires energy and this is where the "missing" kinetic energy goes. A classic example of an inelastic collision is a motor car accident. The cars change shape and there is a noticeable change in the kinetic energy of the cars before and after the collision. This energy was used to bend the metal and deform the cars. Another example of an inelastic collision is shown in 2.6.

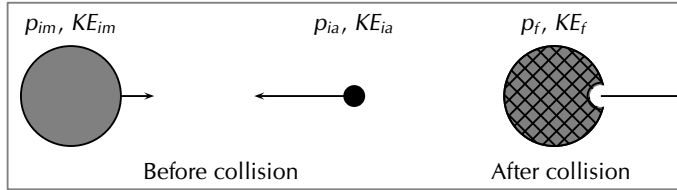



Figure 2.6: Asteroid moving towards the Moon.

An asteroid is moving through space towards the Moon. Before the asteroid crashes into the Moon, the total momentum of the system is:

$$\vec{p}_{Ti} = \vec{p}_{iM} + \vec{p}_{ia}$$

The total kinetic energy of the system is:

$$KE_i = KE_{iM} + KE_{ia}$$

When the asteroid collides **inelastically** with the Moon, its kinetic energy is transformed mostly into heat energy. If this heat energy is large enough, it can cause the asteroid and the area of the Moon's surface that it hits, to melt into liquid rock. From the force of impact of the asteroid, the molten rock flows outwards to form a crater on the Moon.

After the collision, the total momentum of the system will be the same as before. But since this collision is *inelastic*, (and you can see that a change in the shape of objects has taken place), total kinetic energy is **not** the same as before the collision.

Momentum is conserved:

$$\vec{p}_{Ti} = \vec{p}_{Tf}$$

But the total kinetic energy of the system is not conserved:

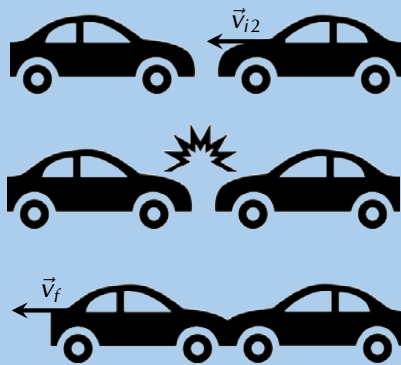
$$KE_i \neq KE_f$$

**Worked example 14: An inelastic collision**

***QUESTION***

Consider the collision of two cars. Car 1 is at rest and Car 2 is moving at a speed of 2 $m \cdot s^{-1}$ to the left. Both cars each have a mass of 500 kg. The cars collide *inelastically* and stick together. What is the resulting velocity of the resulting mass of metal?

***SOLUTION***

**Step 1: Draw a rough sketch of the situation**

**Step 2: Determine how to approach the problem**

We are given:

- mass of car 1, $m_1 = 500kg$
- mass of car 2, $m_2 = 500kg$
- initial velocity of car 1, $\vec{v}_{i1} = 0ms^{-1}$
- initial velocity of car 2, $\vec{v}_{i2} = 2ms^{-1}$ to the left
- the collision is inelastic

All quantities are in SI units. We are required to determine the final velocity of the resulting mass, $\vec{v}_f$.
Since the collision is inelastic, we know that

- momentum is conserved, $m_1\vec{v}_{i1} + m_2\vec{v}_{i2} = m_1\vec{v}_{f1} + m_2\vec{v}_{f2} = (m_1 + m_2)\,\vec{v}_f$
- kinetic energy is not conserved

**Step 3: Choose a frame of reference**

Choose to the left as positive.

**Step 4: Solve problem**

So we must use conservation of momentum to solve this problem.

$$\begin{aligned}
\vec{p}_{Ti} &= \vec{p}_{Tf} \\
\vec{p}_{i1} + \vec{p}_{i2} &= \vec{p}_f \\
m_1\vec{v}_{i1} + m_2\vec{v}_{i2} &= (m_1 + m_2)\,\vec{v}_f \\
(500)(0) + (500)(2) &= (500 + 500)\,\vec{v}_f \\
1000 &= 1000\vec{v}_f \\
\vec{v}_f &= 1 m \cdot s^{-1}
\end{aligned}$$

Therefore, the final velocity of the resulting mass of cars is 1 $m \cdot s^{-1}$ to the left.

**Exercise 2 – 4: Collisions**

1. A truck of mass 4500 kg travelling at 20 m·s$^{-1}$ hits a car from behind. The car (mass 1000 kg) was travelling at 15 m·s$^{-1}$. The two vehicles, now connected carry on moving in the same direction.
   a) Calculate the final velocity of the truck-car combination after the collision.
   b) Determine the kinetic energy of the system before and after the collision.
   c) Explain the difference in your answers for b).
   d) Was this an example of an elastic or inelastic collision? Give reasons for your answer.
2. Two cars of mass 900 kg each collide head-on and stick together. Determine the final velocity of the cars if car 1 was travelling at 15 m·s$^{-1}$ and car 2 was travelling at 20 m·s$^{-1}$.
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27HW  2. 27HX

 www.everythingscience.co.za 

## 2.5 Impulse ESCJK

When a net force acts on a body it will result in an acceleration which alters the motion of the body. A large net force will cause a larger acceleration than a small net force. The total change in motion of the object can be the same if the large and small forces act for different time intervals. The combination of the force and time that it acts is a useful quantity which leads us to define impulse.

**DEFINITION:** *Impulse*

Impulse is the product of the net force and the time interval for which the force acts.

$$\text{Impulse} = \vec{F}_{net} \cdot \Delta t$$

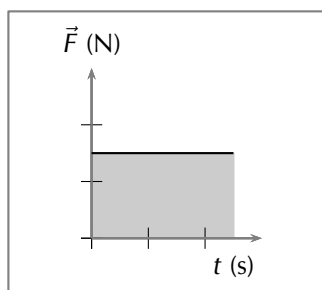
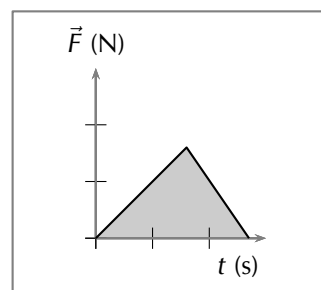
However, from Newton's Second Law, we know that

$$\begin{aligned} \vec{F}_{net} &= \frac{\Delta \vec{p}}{\Delta t} \\ \therefore \vec{F}_{net} \cdot \Delta t &= \Delta \vec{p} \\ &= \text{Impulse} \end{aligned}$$

Therefore we can define the impulse-momentum theorem:

$$\text{Impulse} = \Delta \vec{p}$$

Impulse is equal to the change in momentum of an object. From this equation we see, that for a given change in momentum, $\vec{F}_{net}\Delta t$ is fixed. Thus, if $\vec{F}_{net}$ is reduced, $\Delta t$ must be increased (i.e. a smaller resultant force must be applied for longer to bring about the same change in momentum). Alternatively if $\Delta t$ is reduced (i.e. the resultant force is applied for a shorter period) then the resultant force must be increased to bring about the same change in momentum.

The graphs below show how the force acting on a body changes with time.

The area under the graph, shaded in, represents the impulse of the body.

**Worked example 15: Impulse and change in momentum**

***QUESTION***

A 150 N resultant force acts on a 300 kg trailer. Calculate how long it takes this force to change the trailer's velocity from 2 m·s$^{-1}$ to 6 m·s$^{-1}$ in the same direction. Assume that the forces acts to the right which is the direction of motion of the trailer.

***SOLUTION***

**Step 1: Identify what information is given and what is asked for**

The question explicitly gives

- the trailer's mass as 300 kg,
- the trailer's initial velocity as 2 m·s$^{-1}$ to the right,
- the trailer's final velocity as 6 m·s$^{-1}$ to the right, and
- the resultant force acting on the object.

We are asked to calculate the time taken $\Delta t$ to accelerate the trailer from the 2 to 6 m·s$^{-1}$. From the Newton's second law,

$$\begin{aligned} \vec{F}_{net}\Delta t &= \Delta \vec{p} \\ &= m\vec{v}_f - m\vec{v}_i \\ \Delta t &= \frac{m}{\vec{F}_{net}}\left(\vec{v}_f - \vec{v}_i\right). \end{aligned}$$

Thus we have everything we need to find $\Delta t$!

**Step 2: Choose a frame of reference**

Choose right as the positive direction.

**Step 3: Do the calculation and quote the final answer**

$$\begin{aligned} \Delta t &= \frac{m}{\vec{F}_{net}}\left(\vec{v}_f - \vec{v}_i\right) \\ \Delta \text{t} &= \left(\frac{300}{+150}\right)((+6\ ) - (+2\ )) \\ \Delta \text{t} &= \left(\frac{300}{150}\right)(4\ ) \\ \Delta t &= \frac{(300)\,(+4\ )}{150} \\ \Delta t &= 8 \text{ s} \end{aligned}$$

It takes 8 s for the force to change the object's velocity from 2 m·s$^{-1}$ to the right to 6 m·s$^{-1}$ to the right.

**Worked example 16: Impulsive cricketers**

*QUESTION*

A cricket ball weighing 156 g is moving at 54 km·hr$^{-1}$ towards a batsman. It is hit by the batsman back towards the bowler at 36 km·hr$^{-1}$. Calculate

1. the ball's impulse, and
2. the average force exerted by the bat if the ball is in contact with the bat for 0,13 s.

*SOLUTION*

**Step 1: Identify what information is given and what is asked for**

The question explicitly gives

- the ball's mass,
- the ball's initial velocity,
- the ball's final velocity, and
- the time of contact between bat and ball

We are asked to calculate the impulse:

$$\text{Impulse} = \Delta\vec{p} = \vec{F}_{\text{net}}\Delta t$$

Since we do not have the force exerted by the bat on the ball ( $\vec{F}_{\text{net}}$), we have to calculate the impulse from the change in momentum of the ball. Now, since

$$\begin{aligned}\Delta\vec{p} &= \vec{p}_f - \vec{p}_i \\ &= m\vec{v}_f - m\vec{v}_i,\end{aligned}$$

we need the ball's mass, initial velocity and final velocity, which we are given.

**Step 2: Convert to S.I. units**

Firstly let us change units for the mass

$$\begin{aligned}1000\text{ g} &= 1\text{ kg} \\ \text{So, } 1\text{ g} &= \frac{1}{1000}\text{ kg} \\ \therefore 156 \times 1\text{ g} &= 156 \times \frac{1}{1000}\text{ kg} \\ &= 0{,}156\text{ kg}\end{aligned}$$

Next we change units for the velocity

$$\begin{aligned}1\text{ km}\cdot\text{h}^{-1} &= \frac{1000\text{ m}}{3600\text{ s}} \\ \therefore 54 \times 1\text{ km}\cdot\text{h}^{-1} &= 54 \times \frac{1000\text{ m}}{3600\text{ s}} \\ &= 15\text{ m}\cdot\text{s}^{-1}\end{aligned}$$

Similarly, 36 km·hr$^{-1}$ = 10 m·s$^{-1}$.

**Step 3: Choose a frame of reference**

Let us choose the direction from the batsman to the bowler as the positive direction. Then the initial velocity of the ball is $\vec{v}_i = -15$ m·s$^{-1}$, while the final velocity of the ball is $\vec{v}_f = +10$ m·s$^{-1}$.

**Step 4: Calculate the momentum**

Now we calculate the change in momentum,

$$\begin{aligned}\Delta\vec{p} &= \vec{p}_f - \vec{p}_i \\ &= m\vec{v}_f - m\vec{v}_i \\ &= m\left(\vec{v}_f - \vec{v}_i\right) \\ &= (0{,}156)\left((+10\ ) - (-15\ )\right) \\ &= +3{,}9 \\ &= 3{,}9\text{ kg}\cdot\text{m}\cdot\text{s}^{-1}\text{ in the direction from the batsman to the bowler}\end{aligned}$$

**Step 5: Determine the impulse**

Finally since impulse is just the change in momentum of the ball,

$$\begin{aligned} \text{Impulse} &= \Delta\vec{p} \\ &= 3{,}9\ \text{kg}\cdot\text{m}\cdot\text{s}^{-1} \text{ in the direction from the batsman to the bowler} \end{aligned}$$

**Step 6: Determine the average force exerted by the bat**

Impulse $= \vec{F}_{net}\Delta t = \Delta\vec{p}$

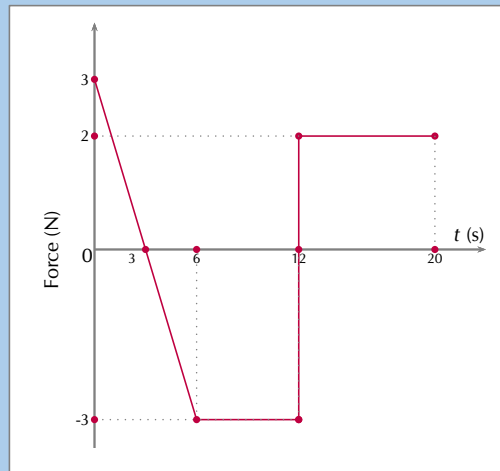
We are given $\Delta t$ and we have calculated the impulse of the ball.

$$\begin{aligned} \vec{F}_{net}\Delta t &= \text{Impulse} \\ \vec{F}_{net}\,(0{,}13) &= +3{,}9 \\ \vec{F}_{net} &= \frac{+3{,}9}{0{,}13} \\ &= +30 \\ &= 30\ \text{N in the direction from the batsman to the bowler} \end{aligned}$$

**Worked example 17: Analysing a force graph**

***QUESTION***

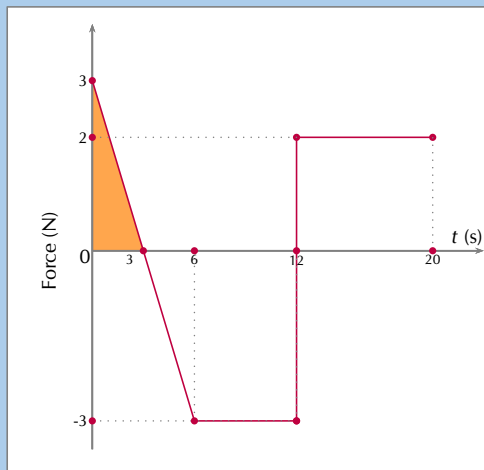
Analyse the Force vs. time graph provided and answer the following questions:

- What is the impulse for the interval 0 s to 3 s?
- What is the impulse for the interval 3 s to 6 s?
- What is the change in momentum for the interval 0 s to 6 s?
- What is the impulse for the interval 6 s to 20 s?
- What is the impulse for the interval 0 s to 20 s?

***SOLUTION***

**Step 1: Identify what information is given and what is being asked for**

A graph of force versus time is provided. We are asked to determine both impulse and change in momentum from it. We know that the area under the graph is the impulse and we can relate impulse to change in momentum with the impulse-momentum theorem.

We need to calculate the area under the graph for the various intervals to determine impulse and then work from there.

**Step 2: Impulse for interval 0 s to 3 s**

We need to calculate the area of the shaded portion under the graph. This is a triangle with a base of 3 s and a height of 3 N therefore:

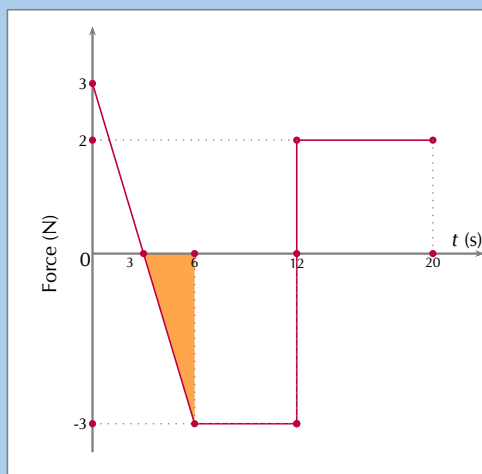
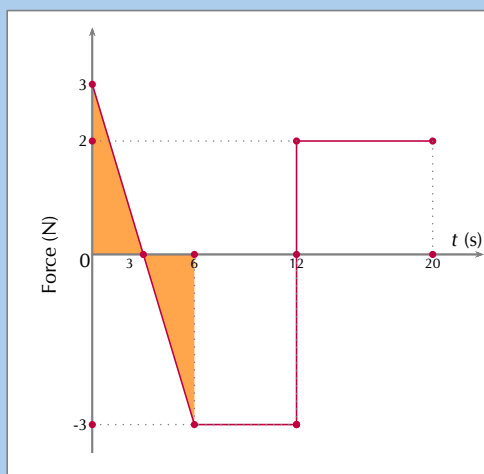
$$
\begin{aligned}
\text{Impulse} &= \frac{1}{2}bh \\
&= \frac{1}{2}(3)(3) \\
&= 4{,}5 \text{ N·s}
\end{aligned}
$$

The impulse is 4,5 N·s in the positive direction.

**Step 3: Impulse for interval 3 s to 6 s**

We need to calculate the area of the shaded portion under the graph. This is a triangle with a base of 3 s and a height of $-3$ N. Note that the force has a negative value so is pointing in the negative direction.

$$
\begin{aligned}
\text{Impulse} &= \frac{1}{2}bh \\
&= \frac{1}{2}(3)(-3) \\
&= -4{,}5 \text{ N·s}
\end{aligned}
$$

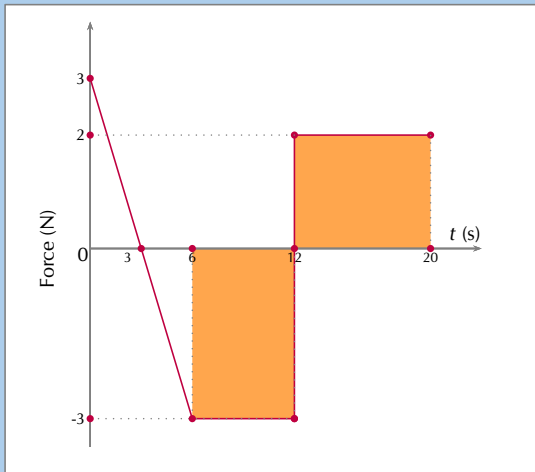
The impulse is 4,5 N·s in the negative direction.

**Step 4: What is the change in momentum for the interval 0 s to 6 s**

From the impulse-momentum theorem we know that that impulse is equal to the change in momentum. We have worked out the impulse for the two sub-intervals making up 0 s to 6 s. We can sum them to find the impulse for the total interval:

$$
\begin{aligned}
\text{impulse}_{0-6} &= \text{impulse}_{0-3} + \text{impulse}_{3-6} \\
&= (4{,}5) + (-4{,}5) \\
&= 0 \text{ N·s}
\end{aligned}
$$

The positive impulse in the first 3 seconds is exactly opposite to the impulse in the second 3 second interval making the total impulse for the first 6 seconds zero:

From the impulse-momentum theorem we know that:

$$\Delta\vec{p} = \text{impulse} = 0 \text{ N·s}$$

**Step 5: What is the impulse for the interval 6 s to 20 s**

We need to calculate the area of the shaded portion under the graph. This is divided into two areas, 6 s to 12 s and 12 s to 20 s, which we need to sum to get the total impulse.

$$\begin{aligned} \text{Impulse}_{6-12} &= (6)(-3) \\ &= -18 \text{ N·s} \end{aligned}$$

$$\begin{aligned} \text{Impulse}_{12-20} &= (8)(2) \\ &= +16 \text{ N·s} \end{aligned}$$

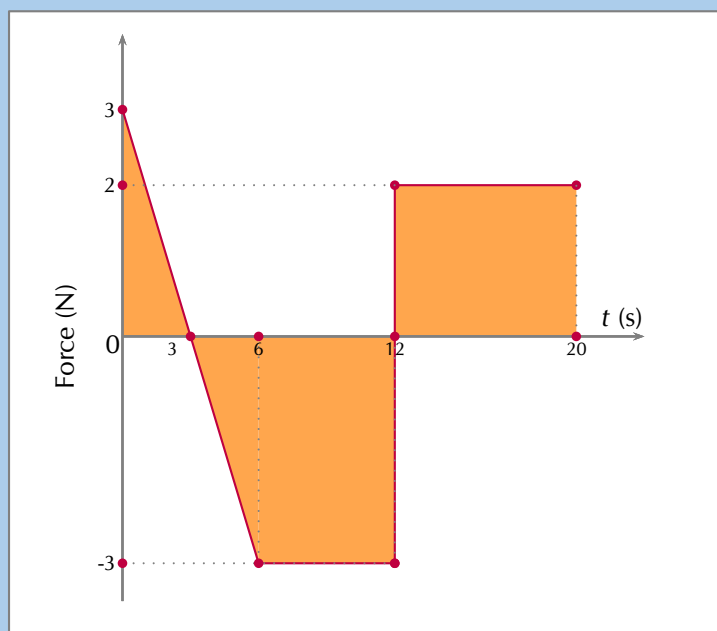
The total impulse is the sum of the two:

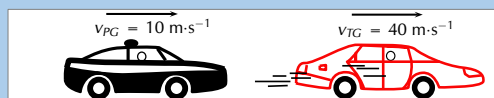
$$\begin{aligned} \text{Impulse}_{6-20} &= \text{Impulse}_{6-12} + \text{Impulse}_{12-20} \\ &= (-18) + (16) \\ &= -2 \text{ N·s} \end{aligned}$$

The impulse is 2 N·s in the negative direction.

**Step 6: What is the impulse of the entire period**

The impulse is 2 N·s in the negative direction.

**Worked example 18: Car chase [Excerpt from NSC 2011 Paper 1]**

***QUESTION***

A patrol car is moving on a straight horizontal road at a velocity of 10 m·s$^{-1}$ east. At the same time a thief in a car ahead of him is driving at a velocity of 40 m·s$^{-1}$ in the same direction.

$v_{PG}$: velocity of the **patrol** car relative to the **ground**
$v_{TG}$: velocity of the **thief**'s car relative to the **ground**

**Questions 1 and 2 from the original version in 2011 Paper 1 are no longer part of the curriculum.**

1. While travelling at 40 m·s$^{-1}$, the thief's car of mass 1000 kg, collides head-on with a truck of mass 5000 kg moving at 20 m·s$^{-1}$. After the collision, the car and the truck move together. Ignore the effects of friction.

   State the *law of conservation of linear momentum* in words.

   (2 marks)
2. Calculate the velocity of the thief's car immediately after the collision.

   (6 marks)
3. Research has shown that forces greater than 85 000 N during collisions may cause fatal injuries. The collision described above lasts for 0,5 s.

   Determine, by means of a calculation, whether the collision above could result in a fatal injury.

   (5 marks)

**[TOTAL: 13 marks]**

***SOLUTION***

**Question 1**

The total (linear) momentum remains constant (**OR** is conserved **OR** does not change) in an isolated (**OR** in a closed system **OR** in the absence of external forces).

(2 marks)

**Question 2**

**Option 1:**

Taking to the right as positive

$$\begin{aligned} \sum p_{\text{before}} &= \sum p_{\text{after}} \\ (1000)(40) + (5000)(-20) &= (1000 + 5000)v_f \\ v_f &= -10\ \text{m}\cdot\text{s}^{-1} \\ &= 10\ \text{m}\cdot\text{s}^{-1} \quad \text{left OR west} \end{aligned}$$

**Option 2:**

Taking to the right as positive

$$\begin{aligned} \Delta p_{\text{car}} &= -\Delta p_{\text{truck}} \\ m_{\text{car}}(v_f - v_{i,\text{car}}) &= -m_{\text{truck}}(v_f - v_{i,\text{truck}}) \\ (1000)(v_f - (40)) &= -(5000)(v_f - (-20)) \\ 6000v_f &= -60\ 000 \\ \therefore v_f &= -10\ \text{m}\cdot\text{s}^{-1} \\ \therefore v_f &= 10\ \text{m}\cdot\text{s}^{-1} \quad \text{left OR west} \end{aligned}$$

(6 marks)

**Question 3**

**Option 1:**
Force on the car: (Taking to the right as positive)

$$\begin{aligned} F_{\text{net}}\Delta t &= \Delta p = mv_f - mv_i \\ F_{\text{net}}(0{,}5) &= (1000)(-10 - 40) \\ \therefore F_{\text{net}} &= -10^5\ \text{N} \\ &\text{OR} \\ \therefore F_{\text{net}} &= 10^5\ \text{N} \quad (100\ 000\ \text{N}) \\ \therefore F_{\text{net}} &> 85\ 000\ \text{N} \end{aligned}$$

Yes, the collision is fatal.
**OR**
Force on the car: (Taking to the left as positive)

$$\begin{aligned} F_{\text{net}}\Delta t &= \Delta p = mv_f - mv_i \\ F_{\text{net}}(0{,}5) &= (1000)(10 - (-40)) \\ \therefore F_{\text{net}} &= 10^5\ \text{N} \quad (100\ 000\ \text{N}) \\ \therefore F_{\text{net}} &> 85\ 000\ \text{N} \end{aligned}$$

Yes, the collision is fatal.

**Option 2:**
Force on the truck: (Taking to the right as positive)

$$\begin{aligned} F_{\text{net}}\Delta t &= \Delta p = mv_f - mv_i \\ F_{\text{net}}(0{,}5) &= (5000)(-10 - (-20)) \\ \therefore F_{\text{net}} &= 10^5\ \text{N} \quad (100\ 000\ \text{N}) \\ \therefore F_{\text{net}} &> 85\ 000\ \text{N} \end{aligned}$$

Yes, the collision is fatal.
**OR**
Force on the truck: (Taking to the left as positive)

$$\begin{aligned} F_{\text{net}}\Delta t &= \Delta p = mv_f - mv_i \\ F_{\text{net}}(0{,}5) &= (1000)(10 - 20) \\ \therefore F_{\text{net}} &= -10^5\ \text{N} \\ &\text{OR} \\ \therefore F_{\text{net}} &= 10^5\ \text{N} \quad (100\ 000\ \text{N}) \\ \therefore F_{\text{net}} &> 85\ 000\ \text{N} \end{aligned}$$

Yes, the collision is fatal.

**Option 3:**
Force on the car: (Taking to the right as positive)

$$\begin{aligned} v_f &= v_i + a\Delta t \\ -10 &= 40 + a(0,5) \\ \therefore a &= -100 \text{ m} \cdot \text{s}^{-2} \\ F_{\text{net}} &= ma \\ &= (1000)(-100) \\ F_{\text{net}} &= -10^5 \text{ N} \quad (-100\ 000 \text{ N}) \\ F_{\text{net}} &= 10^5 \text{ N} \quad (100\ 000 \text{ N}) \\ \therefore F_{\text{net}} &> 85\ 000 \text{ N} \end{aligned}$$

Yes, the collision is fatal.
**OR**
Force on the car: (Taking to the left as positive)

$$\begin{aligned} v_f &= v_i + a\Delta t \\ 10 &= -40 + a(0,5) \\ \therefore a &= 100 \text{ m} \cdot \text{s}^{-2} \\ F_{\text{net}} &= ma \\ &= (1000)(100) \\ F_{\text{net}} &= 10^5 \text{ N} \quad (100\ 000 \text{ N}) \\ \therefore F_{\text{net}} &> 85\ 000 \text{ N} \end{aligned}$$

Yes, the collision is fatal.

**Option 4:**
Force on the truck: (Taking to the right as positive)

$$\begin{aligned} v_f &= v_i + a\Delta t \\ -10 &= -20 + a(0,5) \\ \therefore a &= 20 \text{ m} \cdot \text{s}^{-2} \\ F_{\text{net}} &= ma \\ &= (5000)(20) \\ F_{\text{net}} &= 10^5 \text{ N} \quad (100\ 000 \text{ N}) \\ \therefore F_{\text{net}} &> 85\ 000 \text{ N} \end{aligned}$$

Yes, the collision is fatal.
**OR**
Force on the truck: (Taking to the left as positive)

$$\begin{aligned} v_f &= v_i + a\Delta t \\ 10 &= 20 + a(0,5) \\ \therefore a &= -20 \text{ m} \cdot \text{s}^{-2} \\ F_{\text{net}} &= ma \\ &= (5000)(-20) \\ F_{\text{net}} &= -10^5 \text{ N} \quad (-100\ 000 \text{ N}) \\ F_{\text{net}} &= 10^5 \text{ N} \quad (100\ 000 \text{ N}) \\ \therefore F_{\text{net}} &> 85\ 000 \text{ N} \end{aligned}$$

Yes, the collision is fatal.
(5 marks)

**[TOTAL: 13 marks]**

**Exercise 2 – 5:**

1. Which one of the following is **not** a unit of impulse?
   a) N·s
   b) $\text{kg}\cdot\text{m}\cdot\text{s}^{-1}$
   c) $\text{J}\cdot\text{m}\cdot\text{s}^{-1}$
   d) $\text{J}\cdot\text{m}^{-1}\cdot\text{s}$
2. A toy car of mass 1 kg moves eastwards with a speed of 2 $\text{m}\cdot\text{s}^{-1}$. It collides head-on with a toy train. The train has a mass of 2 kg and is moving at a speed of 1,5 $\text{m}\cdot\text{s}^{-1}$ westwards. The car rebounds (bounces back) at 3,4 $\text{m}\cdot\text{s}^{-1}$ and the train rebounds at 1,2 $\text{m}\cdot\text{s}^{-1}$.
   a) Calculate the change in momentum for each toy.
   b) Determine the impulse for each toy.

c) Determine the duration of the collision if the magnitude of the force exerted by each toy is 8 N.

3. A bullet of mass 20 g strikes a target at 300 $m \cdot s^{-1}$ and exits at 200 $m \cdot s^{-1}$. The tip of the bullet takes 0,0001 s to pass through the target. Determine:
   a) the change of momentum of the bullet.
   b) the impulse of the bullet.
   c) the magnitude of the force experienced by the bullet.
4. A bullet of mass 20 g strikes a target at 300 $m \cdot s^{-1}$. Determine under which circumstances the bullet experiences the greatest change in momentum, and hence impulse:
   a) When the bullet exits the target at 200 $m \cdot s^{-1}$.
   b) When the bullet stops in the target.
   c) When the bullet rebounds at 200 $m \cdot s^{-1}$.
5. A ball with a mass of 200 g strikes a wall at right angles at a velocity of 12 $m \cdot s^{-1}$ and rebounds at a velocity of 9 $m \cdot s^{-1}$.
   a) Calculate the change in the momentum of the ball.
   b) What is the impulse of the wall on the ball?
   c) Calculate the magnitude of the force exerted by the wall on the ball if the collision takes 0,02 s.
6. If the ball in the previous problem is replaced with a piece of clay of 200 g which is thrown against the wall with the same velocity, but then sticks to the wall, calculate:
   a) The impulse of the clay on the wall.
   b) The force exerted by the clay on the wall if it is in contact with the wall for 0,5 s before it comes to rest.
7. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27HY  2. 27HZ  3. 27J2  4. 27J3  5. 27J4  6. 27J5

## 2.6 Physics in action: Impulse ESCJM

A very important application of impulse is improving safety and reducing injuries. In many cases, an object needs to be brought to rest from a certain initial velocity. This means there is a certain specified change in momentum. If the time during which the momentum changes can be increased then the force that must be applied will be less and so it will cause less damage. This is the principle behind arrestor beds for trucks, airbags, and bending your knees when you jump off a chair and land on the ground.

## Air-bags in motor vehicles ESCJN

Air bags are used in motor vehicles because they are able to reduce the effect of the force experienced by a person during an accident. Air bags extend the time required to stop the momentum of the driver and passenger. During a collision, the motion of the driver and passenger carries them towards the windshield. If they are stopped by a collision with the windshield, it would result in a large force exerted over a short time in order to bring them to a stop. If instead of hitting the windshield, the driver and passenger hit an air bag, then the time of the impact is increased. Increasing the time of the impact results in a decrease in the force.

$$F = \frac{\Delta p}{\Delta t}$$

Therefore if t is increased, for a constant change in momentum, force on body is reduced

## Padding as protection during sports ESCJP

The same principle explains why wicket keepers in cricket use padded gloves or why there are padded mats in gymnastics. In cricket, when the wicket keeper catches the ball, the padding is slightly compressible, thus reducing the effect of the force on the wicket keepers hands. Similarly, if a gymnast falls, the padding compresses and reduces the effect of the force on the gymnast's body.

## Arrestor beds for trucks ESCJQ

An arrestor bed is a patch of ground that is softer than the road. Trucks use these when they have to make an emergency stop. When a trucks reaches an arrestor bed the time interval over which the momentum is changed is increased. This decreases the force and causes the truck to slow down.

## Follow-through in sports ESCJR

In sports where rackets and bats are used, like tennis, cricket, squash, badminton and baseball, the hitter is often encouraged to follow-through when striking the ball. High speed films of the collisions between bats/rackets and balls have shown that following through increases the time over which the collision between the racket/bat and ball occurs. This increase in the time of the collision causes an increase in the velocity change of the ball. This means that a hitter can cause the ball to leave the racket/bat faster by following through. In these sports, returning the ball with a higher velocity often increases the chances of success.

## Crumple zones in cars

Another safety application of trying to reduce the force experienced is in crumple zones in cars. When two cars have a collision, two things can happen:

1. the cars bounce off each other, or
2. the cars crumple together.

Which situation is more dangerous for the occupants of the cars? When cars bounce off each other, or rebound, there is a larger change in momentum and therefore a larger impulse. A larger impulse means that a greater force is experienced by the occupants of the cars. When cars crumple together, there is a smaller change in momentum and therefore a smaller impulse. The smaller impulse means that the occupants of the cars experience a smaller force. Car manufacturers use this idea and design crumple zones into cars, such that the car has a greater chance of crumpling than rebounding in a collision. Also, when the car crumples, the change in the car's momentum happens over a longer time. Both these effects result in a smaller force on the occupants of the car, thereby increasing their chances of survival.

**Activity: Egg Throw**

This activity demonstrates the effect of impulse and how it is used to improve safety. Have two learners hold up a bed sheet or large piece of fabric. Then toss an egg at the sheet. The egg should not break, because the collision between the egg and the bed sheet lasts over an extended period of time since the bed sheet has some give in it. By increasing the time of the collision, the force of the impact is minimised. Take care to aim at the sheet, because if you miss the sheet, you will definitely break the egg and have to clean up the mess!

**Exercise 2 – 6:**

1. A canon, mass 500 kg, fires a shell, mass 1 kg, horizontally to the right at 500 $m{\cdot}s^{-1}$. What is the magnitude and direction of the initial recoil velocity of the canon?
2. A trolley of mass 1 kg is moving with a speed of 3 $m{\cdot}s^{-1}$. A block of wood, mass 0,5 kg, is dropped vertically into the trolley. Immediately after the collision, the speed of the trolley and block is 2 $m{\cdot}s^{-1}$. By way of calculation, show whether momentum is conserved in the collision.
3. A 7200 kg empty railway truck is stationary. A fertiliser firm loads 10 800 kg fertiliser into the truck. A second, identical, empty truck is moving at 10 $m{\cdot}s^{-1}$ when it collides with the loaded truck.

   a) If the empty truck stops completely immediately after the collision, use a conservation law to calculate the velocity of the loaded truck immediately after the collision.

b) Calculate the distance that the loaded truck moves after collision, if a constant frictional force of 24 kN acts on the truck.

4. A child drops a squash ball of mass 0,05 kg. The ball strikes the ground with a velocity of 4 m·s$^{-1}$ and rebounds with a velocity of 3 m·s$^{-1}$. Considering only the squash ball, does the law of conservation of momentum apply to this situation? Explain.
5. A bullet of mass 50 g travelling horizontally at 600 m·s$^{-1}$ strikes a stationary wooden block of mass 2 kg resting on a smooth horizontal surface. The bullet gets stuck in the block.
   a) Name and state the principle which can be applied to find the speed of the block-and-bullet system after the bullet entered the block.
   b) Calculate the speed of the bullet-and-block system immediately after impact.
   c) If the time of impact was $5 \times 10^{-4}$ s, calculate the force that the bullet exerts on the block during impact.
6. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27J6   2. 27J7   3. 27J8   4. 27J9   5. 27JB

 www.everythingscience.co.za   

## 2.7 Chapter summary ESCJT

See presentation: 27JC at www.everythingscience.co.za

- **Newton's Second Law:** The resultant force acting on a body will cause the body to accelerate in the direction of the resultant force The acceleration of the body is directly proportional to the magnitude of the resultant force and inversely proportional to the mass of the object.
- **Newton's Third Law:** If body A exerts a force on body B then body B will exert an equal but opposite force on body A.
- **Momentum:** The *momentum* of an object is defined as its mass multiplied by its velocity.
- **Momentum of a System:** The *total momentum of a system* is the sum of the momenta of each of the objects in the system.
- **Principle of Conservation of Linear Momentum:** 'The total linear momentum of an isolated system is constant' or 'In an isolated system the total momentum before a collision (or explosion) is equal to the total momentum after the collision (or explosion)'.
- **Elastic collision:** both total momentum and total kinetic energy are conserved.
- **Inelastic collision:** only total momentum is conserved, total kinetic energy is not conserved.
- **Impulse:**the product of the net force and the time interval for which the force acts.
- **Law of Momentum:** The applied resultant force acting on an object is equal to

the rate of change of the object's momentum and this force is in the direction of the change in momentum.

- **Impulse-momentum theorem:** the impulse is equal to the change in momentum.

| Physical quantities | | | |
|---|---|---|---|
| **Quantity** | **Vector** | **Unit name** | **Unit symbol** |
| Mass ($m$) | - | kilogram | kg |
| Velocity ($\vec{v}$) | ✓ | metre per second | m·s$^{-1}$ |
| Momentum ($\vec{p}$) | ✓ | kilogram metres per second | kg·m·s$^{-1}$ |
| Kinetic energy ($KE$) | - | joule | J |
| Impulse | ✓ | newton seconds | N·s |

Table 2.1: Units used in **momentum and impulse**.

### Exercise 2 – 7: Momentum

1. [SC 2003/11]A projectile is fired vertically upwards from the ground. At the highest point of its motion, the projectile explodes and separates into two pieces of equal mass. If one of the pieces is projected vertically upwards after the explosion, the second piece will...
   a) drop to the ground at zero initial speed.
   b) be projected downwards at the same initial speed as the first piece.
   c) be projected upwards at the same initial speed as the first piece.
   d) be projected downwards at twice the initial speed as the first piece.
2. [IEB 2004/11 HG1] A ball hits a wall horizontally with a speed of 15 m·s$^{-1}$. It rebounds horizontally with a speed of 8 m·s$^{-1}$. Which of the following statements about the system of the ball and the wall is **true**?
   a) The total linear momentum of the system is not conserved during this collision.
   b) The law of conservation of energy does not apply to this system.
   c) The change in momentum of the wall is equal to the change in momentum of the ball.
   d) Energy is transferred from the ball to the wall.
3. [IEB 2001/11 HG1] A block of mass M collides with a stationary block of mass 2M. The two blocks move off together with a velocity of $\vec{v}$. What is the velocity of the block of mass M immediately **before** it collides with the block of mass 2M?
   a) $\vec{v}$
   b) $2\vec{v}$
   c) $3\vec{v}$
   d) $4\vec{v}$
4. [IEB 2003/11 HG1] A cricket ball and a tennis ball move horizontally towards you with the same momentum. A cricket ball has greater mass than a tennis ball. You apply the same force in stopping each ball.
   How does the time taken to stop each ball compare?

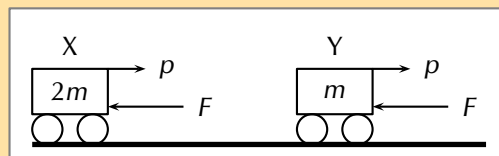
a) It will take longer to stop the cricket ball.
b) It will take longer to stop the tennis ball.
c) It will take the same time to stop each of the balls.
d) One cannot say how long without knowing the kind of collision the ball has when stopping.

5. [IEB 2004/11 HG1] Two identical billiard balls collide head-on with each other. The first ball hits the second ball with a speed of V, and the second ball hits the first ball with a speed of 2V. After the collision, the first ball moves off in the opposite direction with a speed of 2V. Which expression correctly gives the speed of the second ball after the collision?

   a) V
   b) 2V
   c) 3V
   d) 4V

6. [SC 2002/11 HG1] Which one of the following physical quantities is the same as the rate of change of momentum?

   a) resultant force
   b) work
   c) power
   d) impulse

7. [IEB 2005/11 HG] Cart X moves along a smooth track with momentum p. A resultant force F applied to the cart stops it in time t. Another cart Y has only half the mass of X, but it has the same momentum p.

   In what time will cart Y be brought to rest when the same resultant force F acts on it?

   a) $\frac{1}{2}t$
   b) $t$
   c) $2t$
   d) $4t$

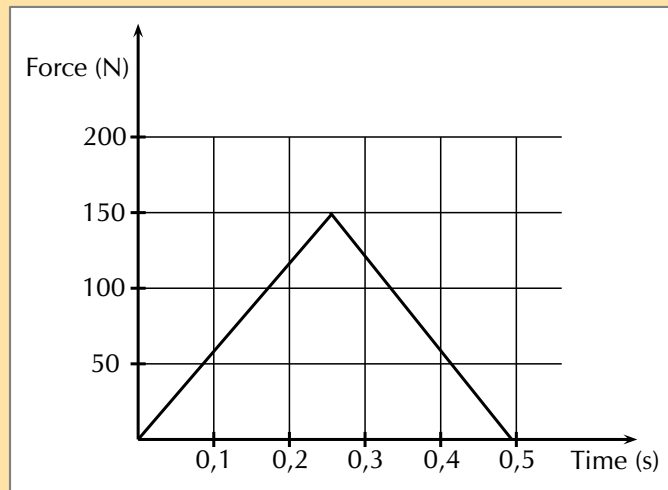
8. [SC 2002/03 HG1] A ball with mass m strikes a wall perpendicularly with a speed, v. If it rebounds in the opposite direction with the same speed, v, the magnitude of the change in momentum will be ...

   a) $2mv$
   b) $mv$
   c) $\frac{1}{2}mv$
   d) $0mv$

9. Show that impulse and momentum have the same units.
10. A golf club exerts an average force of 3 kN on a ball of mass 0,06 kg. If the golf club is in contact with the golf ball for $5 \times 10^{-4}$ seconds, calculate

a) the change in the momentum of the golf ball.

b) the velocity of the golf ball as it leaves the club.

11. During a game of hockey, a player strikes a stationary ball of mass 150 g . The graph below shows how the force of the ball varies with the time.

a) What does the area under this graph represent?

b) Calculate the speed at which the ball leaves the hockey stick.

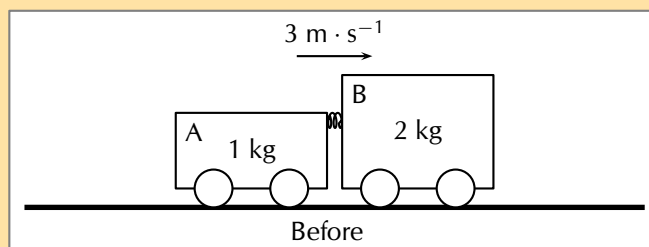
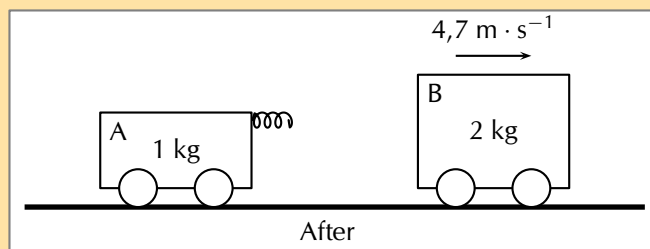
c) The same player hits a practice ball of the same mass, but which is made from a softer material. The hit is such that the ball moves off with the same speed as before. How will the **area**, the **height** and the **base** of the triangle that forms the graph, compare with that of the original ball?

12. The fronts of modern cars are deliberately designed in such a way that in case of a head-on collision, the front would crumple. Why is it desirable that the front of the car should crumple?

13. [SC 2002/11 HG1] In a railway shunting yard, a locomotive of mass 4000 kg, travelling due east at a velocity of 1,5 $m{\cdot}s^{-1}$, collides with a stationary goods wagon of mass 3000 kg in an attempt to couple with it. The coupling fails and instead the goods wagon moves due east with a velocity of 2,8 $m{\cdot}s^{-1}$.

a) Calculate the magnitude and direction of the velocity of the locomotive immediately after collision.

b) Name and state in words the law you used to answer the previous question

14. [SC 2005/11 SG1] A combination of trolley A (fitted with a spring) of mass 1 kg, and trolley B of mass 2 kg, moves to the right at 3 $m{\cdot}s^{-1}$ along a frictionless, horizontal surface. The spring is kept compressed between the two trolleys.

While the combination of the two trolleys is moving at 3 $m{\cdot}s^{-1}$, the spring is released and when it has expanded completely, the 2 kg trolley is then moving to the right at 4,7 $m{\cdot}s^{-1}$ as shown below.

a) State, in words, the principle of *conservation of linear momentum*.

b) Calculate the magnitude and direction of the velocity of the 1 kg trolley immediately after the spring has expanded completely.

15. [IEB 2002/11 HG1] A ball bounces back from the ground. Which of the following statements is true of this event?

    a) The magnitude of the change in momentum of the ball is equal to the magnitude of the change in momentum of the Earth.

    b) The magnitude of the impulse experienced by the ball is greater than the magnitude of the impulse experienced by the Earth.

    c) The speed of the ball before the collision will always be equal to the speed of the ball after the collision.

    d) Only the ball experiences a change in momentum during this event.

16. [SC 2002/11 SG] A boy is standing in a small stationary boat. He throws his schoolbag, mass 2 kg, horizontally towards the jetty with a velocity of 5 $m \cdot s^{-1}$. The *combined mass* of the boy and the boat is 50 kg.

    a) Calculate the magnitude of the horizontal momentum of the bag immediately after the boy has thrown it.

    b) Calculate the velocity (magnitude and direction) of the *boat-and-boy* immediately after the bag is thrown.

17. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

| | | | | | |
|---|---|---|---|---|---|
| 1. 27JD | 2. 27JF | 3. 27JG | 4. 27JH | 5. 27JJ | 6. 27JK |
| 7. 27JM | 8. 27JN | 9. 27JP | 10. 27JQ | 11. 27JR | 12. 27JS |
| 13. 27JT | 14. 27JV | 15. 27JW | 16. 27JX | | |

CHAPTER

# Vertical projectile motion in one dimension

## 3.1 Introduction ESCJV

In this chapter we are going to look at the motion of objects that are either projected, thrown, or shot directly into the air, be it vertically upwards, downwards or when objects are dropped. This is something that everyone has experienced while playing games and we all have a strong intuition that 'what goes up, must come down', but now we'll study why that is the case.

See video: 27JY at www.everythingscience.co.za

**Key linked concepts**

- Units and unit conversions — Physical Sciences, Grade 10, Science skills
- Rectilinear motion — Physical Sciences, Grade 10, Motion in one dimension
- Linear equations — Mathematics, Grade 10, Equations and inequalities
- Quadratic equations — Mathematics, Grade 10, Functions

## 3.2 Vertical projectile motion ESCJW

In Grade 11, we studied the motion of objects in free fall and saw that such an object has a constant gravitational acceleration of $\vec{g}$. We now study the motion of objects that are moving upwards or downwards while experiencing a force due to gravity. We call this projectile motion. We will only consider the case where objects move vertically upwards and/or downwards – meaning that there is no horizontal displacement of the object, only vertical displacement.

When we talk about a projectile we mean a body or particle that is project or launched and then moves under the influence of **only gravity**.

### Motion in a gravitational field ESCJX

We know from Newton's Law of Universal Gravitation that an object in the Earth's gravitational field experiences a force pulling it towards the centre of the Earth. If this is the only force acting on the object then the object will accelerate towards the centre of the Earth.

A person standing on the Earth's surface will interpret this acceleration as objects always falling downwards. In Grade 11, we showed that the value of the acceleration due to gravity can be treated as a having a constant magnitude of $g = 9{,}8\ \text{m}\cdot\text{s}^{-2}$.

**IMPORTANT!**

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In reality, if you go very far away from the Earth's surface, the magnitude of $\vec{g}$ would change, but, for everyday problems, we can safely treat it as constant. We also ignore any effects that air resistance (drag) might have.

---

For the rest of this chapter we will deal only with the case where the force due to gravity is the only force acting on the projectile that is falling. Any projectile can be described as falling, even if its motion is upwards initially.

The initial velocity, $\vec{v}_i$, that an object has and the acceleration that it experiences are two different quantities. It is very important to remember that the gravitational acceleration is always towards the centre of the Earth and constant, regardless of the direction or magnitude of the velocity.

**TIP**
Projectiles moving upwards or downwards in the Earth's gravitational field always accelerate downwards with a constant acceleration $\vec{g}$. Note: non-zero acceleration means that the velocity is *changing*.

**TIP**
Projectiles that have an initial velocity upwards will have zero velocity at their greatest height, $h_{max}$. The acceleration is still $\vec{g}$.

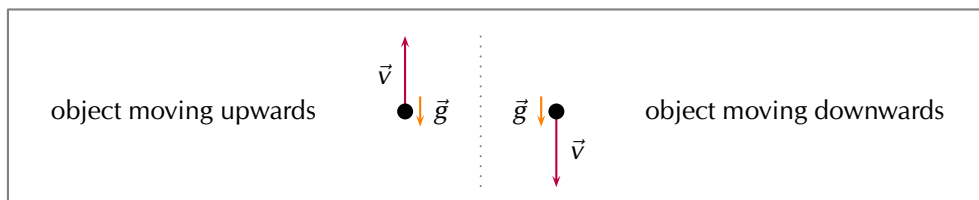



Figure 3.1: Objects moving upwards or downwards in the Earth's gravitational field always accelerate towards the centre of the Earth. This looks like a downwards acceleration to someone standing on the Earth's surface. We don't draw both vectors on the object because we would be mixing velocity and acceleration which are two *different* physical quantities.

See video: 27JZ at www.everythingscience.co.za

This means that if an object is moving upwards with some initial velocity in the vertical direction, the magnitude of the velocity in the vertical direction decreases until it stops ($v = 0$ m·s $^{-1}$) for an instant. The point at which the velocity is reduced to zero corresponds with the maximum height, $h_{max}$, that the object reaches. After this, the object starts to fall. It is very important to remember that the acceleration is constant but the velocity vector has changed in magnitude and direction. At the maximum height where the velocity is zero the acceleration is still $\vec{g}$.

Figure 3.2: (a) An object is thrown upwards from height $h_i$. After time $t_m$, the object reaches its maximum height, and starts to drop downwards. After a time $2t_m$ the object returns to height $h_i$.

Consider an object thrown upwards from a vertical height $h_i$. We have said that the object will travel upwards with decreasing vertical velocity until it stops, and then starts moving vertically downwards. The time that it takes for the object to fall back down

to height $h_i$ is the same as the time taken for the object to reach its maximum height from height $h_i$. This is known as *time symmetry*. This is a consquence of the uniform acceleration the projectile experiences.

This has two implications for projectiles that pass through a point on both the upward and downward part of their motion when in free-fall:

- **time symmetry:** the time intervals during the upward motion and the downward motion are the same, for example it will take the same time to rise from initial position to maximum height as it will to drop back to the initial position. This applies to any point as shown by the pink dot in Figure 3.2. The time interval between the projectile passing the point and being at maximum height is the same, $\Delta t$.
- **magnitude of velocity:** the magnitude of the velocity at the same point on the upward and downward motion will be the same, the direction will be reversed, as indicated by the shaded region in Figure 3.2.

This is very useful when solving problems because if you have any information about the upward motion you can learn something about the downward motion as well and vice versa.

**Formal experiment: Investigate the motion of a falling body**

**Aim:**

To measure the position and time during motion and to use that data to plot a "Position vs Time" and "Velocity vs Time" graph from which we can calculate the magnitude for gravitational acceleration, $\vec{g}$.

**Apparatus:**

- ticker tape apparatus
- ticker timer
- tape
- graph paper
- ruler
- foam cushion

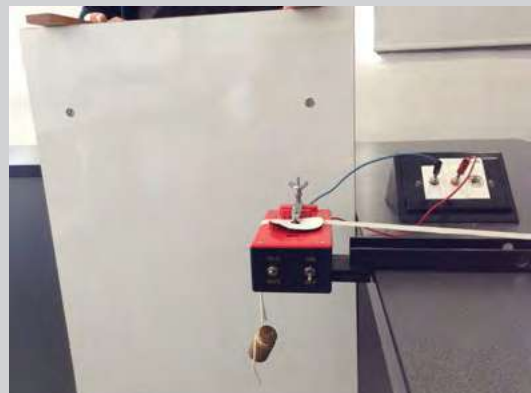



Figure 3.3: Motion at constant velocity

Figure 3.4: Motion with increasing velocity

**Method:**

1. Work with a friend. Copy the table below into your workbook.
2. Clamp the timer to the table to allow the tape to fall through the staples on the timer such that the ticker tape will be perpendicular to the floor. Plug in the timer.
3. Thread a piece of ticker tape through the staples. Make sure the tape is under the carbon disc. The length of the tape should be the distance from the timer to the floor.
4. Using masking tape attach a 100 g mass to the end of the tape closest to the floor.
5. Position the foam cushion directly below the mass. (The cushion will protect your masses and your floor)
6. Hold the tape so that it is vertical and will easily pass through the staples.
7. Turn on the timer.
8. Let go of the tape with the mass, allowing it to drop to the floor.
9. Turn off the timer.
10. Repeat.
11. Take each tape and find the first clear dot nearest the mass end of the tape. Circle this first clear dot and label it as zero. Then count five dots and label the fifth dot as number 1. Count another 5 dots and label the fifth dot number 2. Continue this procedure.
12. On each piece of tape, measure the distance between successive dots. Note these distances in the table below.
13. Use the frequency of the ticker timer to work out the time intervals between successive dots. Note these times in the table below.
14. Work out the average of the two distance values between successive numbered dots.

15. The time interval between two dots is 0,02 s so the time between numbered dots is 0,1 s.
16. Use the average distance between numbered dots and the known time interval to calculate velocity.
17. Use the magnitude of the velocity and time values to plot a graph of "Velocity vs Time" *onto graph paper*. Stick the graph paper into your workbook.
18. Draw the best straight line through your data points.
19. Determine the slope of the straight line. This is the magnitude of the acceleration.

**Results:**

| Change in distance (m) | Change in time (s) | Magnitude of velocity (m·s$^{-1}$) |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

**Discussion:**

Describe the motion of the mass using the graphs.

## Equations of motion ESCJY

The equations of rectilinear motion that you learnt about in Grade 10 can be used for vertical projectile motion, with acceleration from gravity: $\vec{a} = \vec{g}$. Why, because the equations of rectilinear motion can be applied to any motion in a straight line with constant acceleration. If we are only considering vertical motion (up and down) it is motion in a straight line and the acceleration, $\vec{g}$, is constant and along the same line. We use the magnitude of $g = 9{,}8$ m·s $^{-2}$ for our calculations.

**IMPORTANT!**

---

Now would be a good time to revise both rectilinear motion and quadratic equations from Grade 10.

---

Remember that when you use these equations, you are dealing with vectors which have magnitude *and* direction. Therefore, you need to decide which direction will be the positive direction so that your vectors have the correct signs.

The equations of motion that you learnt about in Grade 10 are:

$$\vec{v}_f = \vec{v}_i + \vec{a}t$$
$$\Delta\vec{x} = \frac{(\vec{v}_i + \vec{v}_f)}{2}t$$
$$\Delta\vec{x} = \vec{v}_i t + \frac{1}{2}\vec{a}t^2$$
$$\vec{v}_f^2 = \vec{v}_i^2 + 2\vec{a}\Delta\vec{x}$$

In the case of vertical projectile motion, we know that the only force we will consider is gravity and therefore the acceleration will be $\vec{a} = \vec{g}$.

$$\vec{v}_f = \vec{v}_i + \vec{g}t$$
$$\Delta\vec{x} = \frac{(\vec{v}_i + \vec{v}_f)}{2}t$$
$$\Delta\vec{x} = \vec{v}_i t + \frac{1}{2}\vec{g}t^2$$
$$\vec{v}_f^2 = \vec{v}_i^2 + 2\vec{g}\Delta x$$

where

$\vec{v}_i$ = initial velocity ($m \cdot s^{-1}$) at start

$\vec{v}_f$ = final velocity ($m \cdot s^{-1}$) at time $t$

$\Delta\vec{x}$ = change in vertical position (m)

$t$ = time (s)

$\Delta t$ = time interval (s)

$\vec{a} = \vec{g}$ = acceleration due to gravity ($m \cdot s^{-2}$)

**IMPORTANT!**

$\Delta\vec{x}$ is displacement, the change in position. If the coordinate system you choose isn't centred at the point from which the motion starts (i.e. you don't have $\vec{x}_i = 0$) then you must remember that the displacement and the final position are not the same. The position is given by $\vec{x}_f = \vec{x}_i + \Delta\vec{x}$. If $\vec{x}_i = 0$ then $\vec{x}_f = (0) + \Delta\vec{x}$.

See simulation: 27K2 at www.everythingscience.co.za

Now we can apply this mathematical description of vertical motion to solving problems.

**Worked example 1: Projectile motion**

***QUESTION***

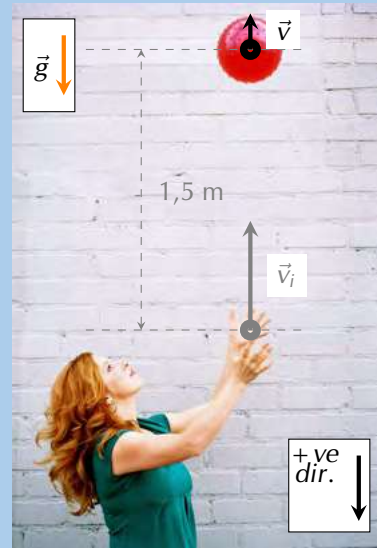
A ball is thrown vertically upwards with an initial velocity of 10 m·s $^{-1}$. A photograph (shown) is taken when the ball is 1,5 m above the point of release.

1. Determine the maximum height above the thrower's hand reached by the ball.
2. Determine the time it takes the ball to reach its maximum height.
3. Determine the time(s) when the ball will be at the position shown in the photograph.

*SOLUTION*

**Step 1: Identify what is required and what is given**

We are required to determine the maximum height reached by the ball and how long it takes to reach this height. We are given the initial velocity $\vec{v}_i = 10$ m·s$^{-1}$ upwards and the acceleration due to gravity $\vec{g} = 9{,}8$ m·s$^{-2}$ downwards. We also need to determine when the ball is at the position shown in the photograph.

The ball is thrown straight up and will reach a maximum height, at which point its velocity will be zero, before beginning to fall downwards. The height of the ball in the photograph is given as 1,5 m above the initial point. Adding the information to the picture helps us understand what is going on more effectively:

**Step 2: Determine how to approach the problem**

Even though there are a number of questions to answer, the best approach is to work through them one at a time.

First, as with rectilinear motion in Grade 10, select a positive direction. We choose **down as positive** and remember to **keep this sign convention** for the whole problem. This will allow us to analyse the information given and determine directions and signs. We know that at the maximum height the velocity of the ball is 0 m·s$^{-1}$. We therefore have the following:

- $\vec{v}_i = -10$ m·s$^{-1}$(it is negative because we chose downwards as positive)
- $\vec{v}_f = 0$ m·s$^{-1}$
- $\vec{g} = 9{,}8$ m·s$^{-2}$

We know that the position shown (1,5 m above the point of release) will be passed as the ball rises to its maximum height and then again as the ball falls downwards.

**Step 3: Identify the appropriate equation to determine the maximum height**

We can use $\vec{v}_f^2 = \vec{v}_i^2 + 2\vec{g}\Delta\vec{x}$ to solve for the height.

**Step 4: Substitute the values into the equation and find the maximum height**

$$\begin{aligned} \vec{v}_f^2 &= \vec{v}_i^2 + 2\vec{g}\Delta\vec{x} \\ (0)^2 &= (-10)^2 + (2)(9{,}8)(\Delta x) \\ -100 &= 19{,}6\Delta x \\ \Delta x &= -5{,}102 \text{ m} \end{aligned}$$

The value for the displacement will be negative because the displacement is upwards and we have chosen downward as positive (and upward as negative). The maximum height will be a positive number, $h_m = 5{,}10$ m.

**Step 5: Identify the appropriate equation to determine the time to reach maximum height**

We know the values of $\vec{v}_i$, $\vec{v}_f$ and $\vec{g}$ so we can use: $\vec{v}_f = \vec{v}_i + \vec{g}t$ to solve for the time.

**Step 6: Substitute the values in and find the time to reach maximum height**

$$\begin{aligned} \vec{v}_f &= \vec{v}_i + \vec{g}t \\ 0 &= -10 + 9{,}8t \\ 10 &= 9{,}8t \\ t &= 1{,}02 \text{ s} \end{aligned}$$

**Step 7: Determine the times at which the ball is in the position in the photograph**

We know the displacement, initial velocity and the acceleration of the ball. We also expect to get two values as we know the ball will pass through the point twice.

We substitute our values into the equation $\Delta\vec{x} = \vec{v}_i t + \frac{1}{2}\vec{g}t^2$, which is a quadratic equation in time, so we expect to find two different solutions if we solve for time.

It is important to notice that we can use the value $-1{,}5$ m as the displacement above the initial position.

$$\begin{aligned} \Delta\vec{x} &= v_i t + \frac{1}{2}\vec{g}t^2 \\ \frac{1}{2}\vec{g}t^2 + \vec{v}_i t - \Delta\vec{x} &= 0 \\ \frac{1}{2}(9{,}8)t^2 + (-10)t - (-1{,}5) &= 0 \\ \underbrace{(4{,}9)}_{a}\underbrace{t^2}_{x^2} + \underbrace{(-10)}_{b}\underbrace{t}_{x} + \underbrace{(1{,}5)}_{c} &= 0 \\ t &= \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \\ t &= \frac{-(-10) \pm \sqrt{(-10)^2 - 4(4{,}9)(1{,}5)}}{2(4{,}9)} \\ t &= \frac{10 \pm \sqrt{70{,}6}}{9{,}8} \\ t &= \frac{10 \pm 8{,}40238}{9{,}8} \\ t &= 1{,}02041 \pm 0{,}857386 \\ t = 0{,}16 \text{ s or } t &= 1{,}88 \text{ s} \end{aligned}$$

**Step 8: Write the final answer**

The ball:

1. reaches a maximum height of 5,10 m;
2. takes 1,02 s to reach the top; and
3. passes through the point in the photograph at $t = 0{,}16$ s on the way up and $t = 1{,}88$ s on the way down.

The use of a sign convention should not affect your result. As an exercise, repeat the

previous worked example using the opposite sign convention to verify that you do get the same result.

**Worked example 2: Height of a projectile**

***QUESTION***

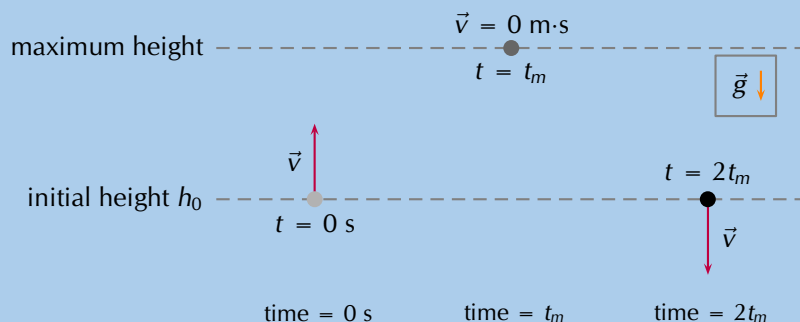
A cricketer hits a cricket ball so that it goes vertically upwards. If the ball takes 10 s to return to the initial height, determine its maximum height above the initial position.

***SOLUTION***

**Step 1: Identify what is required and what is given**

We need to find how high the ball goes. We know that it takes 10 s to go up and down. We do not know what the initial velocity ($\vec{v}_i$) of the ball is. After the batsman strikes the ball it goes directly upwards and the only force that will be acting on the ball will be the gravitational force. This information is represented in the photograph.

**Step 2: Determine how to approach the problem**

For a problem like this it is useful to divide the motion into two parts. The first part of the motion consists of the upward motion of the ball with an initial velocity ($\vec{v}_i$) and a final velocity ($\vec{v}_f = 0$) at the maximum height. The second part of the motion consists of the downward motion of the ball with an initial velocity ($\vec{v}_i = 0$) and final velocity ($\vec{v}_f$) which is not yet known.

**Choose down as positive**. We know that at the maximum height, the velocity of the ball is 0 m·s $^{-1}$. We also know that the ball takes the same time to reach its maximum height as it takes to travel from its maximum height to the initial position, due to time symmetry. The time taken is half the total time. Therefore, we have the following information for the second (downward) part of the motion of the ball:

- $t$ = 5 s (half of the total time)
- $\vec{v}_{top}$ = 0 m·s$^{-1}$
- $\vec{g}$ = 9,8 m·s $^{-2}$ downwards
- $\Delta\vec{x}$ = ?

**Step 3: Find an appropriate equation to use**

We do not know the final velocity of the ball coming down. We need to choose an equation that does not have $\vec{v}_f$ in it. We can use the following equation to solve for $\Delta\vec{x}$:

$$\Delta\vec{x} = \vec{v}_i t + \frac{1}{2}\vec{g}t^2$$

**Step 4: Substitute values and find the height**

$$\Delta\vec{x} = (0)(5) + \frac{1}{2}(9,8)(5)^2$$

$$\Delta\vec{x} = 122,5 \text{ m downwards}$$

In the second motion, the displacement of the ball is 122,5 m downwards. This means that the height was $h$ = 122,5 m.

**Step 5: Write the final answer**

The ball reaches a maximum height of 122,5 m.

**Worked example 3: Equal displacements [attribution: Sunil Kumar Singh]**

***QUESTION***

A sequence of balls are successively dropped from the top of a tower. The time interval between the release of consecutive balls is equal. At the precise instant that the ninth ball (ball 9) is released, the first ball hits the ground. Which of the balls in the sequence is at $\frac{3}{4}$ of the height, $h$, of the tower when the first ball hits the ground?

***SOLUTION***

**Step 1: Understand what is happening**

A ball is dropped from a tower. After a time, $t_i$, a second ball is dropped. After another time interval, $t_i$, a third ball is dropped. This means that when ball 3 is dropped the total time that has passed is $2t_i$.

After a third time interval, $t_i$, a fourth ball is dropped. This means that at the instant that ball 4 is dropped the total time that has passed is $3t_i$. This process continues until the ninth ball is dropped. At the same instant that the ninth ball is dropped, the first ball that was dropped strikes the ground. The ninth ball would have been released after 8 time intervals, therefore it took the first ball a time interval of $8t_i$ to hit the ground.

**Step 2: Describe the events mathematically**

As this is a vertical motion problem where everything is falling towards the ground, it is simplest to choose downwards as the positive direction.

The first ball hits the ground when the ninth ball is dropped. This means that the first

ball has fallen for a total time of $(9-1)t_i = 8t_i$. The displacement of the first ball is also described by the equation $\Delta\vec{x} = \vec{v}_i t + \frac{1}{2}\vec{g}t^2$. The balls are dropped so their initial velocity is zero, $\vec{v}_i = 0$ and the we know the time for the first ball to fall the height of the tower therefore, in the case of the first ball, we have:

$$\begin{aligned}\Delta\vec{x} &= \vec{v}_i t + \frac{1}{2}\vec{g}t^2 \\ h &= \frac{1}{2}(9{,}8)(8t_i)^2\end{aligned}$$

Let the $n$th ball be the ball that is at $\frac{3}{4}$ of the height, $h$, of the tower when the first ball strikes the ground. The $n$th ball will have fall for a time of $(n-1)t_i$. If it is $\frac{3}{4}$ of the way up the tower it will have fall a distance of $\frac{1}{4}h$. This motion is also described by $\Delta\vec{x} = \vec{v}_i t + \frac{1}{2}\vec{g}t^2$, and therefore we know, in the case of the $n$th ball, we have:

$$\begin{aligned}\Delta\vec{x} &= \vec{v}_i t + \frac{1}{2}\vec{g}t^2 \\ \frac{1}{4}h &= \frac{1}{2}(9{,}8)((n-1)t_i)^2 \\ h &= 2(9{,}8)((n-1)t_i)^2\end{aligned}$$

We can't solve for $n$ from this final equation because it will contain $h$ and $t_i$. We can use the two equations we have to eliminate $h$. Both equations are written in the form $h = \ldots$ therefore we can equate them eliminating $h$:

$$\begin{aligned}\frac{1}{2}(9{,}8)(8t_i)^2 &= 2(9{,}8)((n-1)t_i)^2 \\ \frac{1}{2}(9{,}8)8^2t_i^2 &= 2(9{,}8)(n-1)^2t_i^2 \\ \left(\frac{2}{(9{,}8)t_i^2}\right)\times\frac{1}{2}(9{,}8)8^2t_i^2 &= \left(\frac{2}{(9{,}8)t_i^2}\right)\times 2(9{,}8)(n-1)^2t_i^2 \\ 8^2 &= 4(n-1)^2 \\ 8 &= 2(n-1) \\ 4 &= (n-1) \\ n &= 5\end{aligned}$$

**IMPORTANT!**

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We know that $n$ must be a positive integer which is why we use the positive roots when we take the square root above.

---

**Step 3: Write the final answer**

The fifth ball is at $\frac{3}{4}$ of the height of the tower when the first ball strikes the ground.

**Exercise 3 – 1: Equations of motion**

1. A cricketer hits a cricket ball straight up into the air. The cricket ball has an initial velocity of 20 m·s $^{-1}$ vertically upwards.

a) What height does the ball reach before it stops to fall back to the ground.

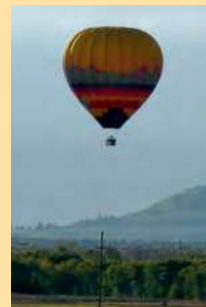
b) How long has the ball been in the air for?

2. Zingi throws a tennis ball straight up into the air. It reaches a height of 80 cm.

   a) Determine the initial velocity of the tennis ball.

   b) How long does the ball take to reach its maximum height?

3. A tourist takes a trip in a hot air balloon. The hot air balloon is ascending (moving up) at a velocity of 4 m·s $^{-1}$ vertically upwards. He accidentally drops his camera over the side of the balloon's basket, at a height of 20 m.
   Calculate the velocity with which the camera hits the ground.

A hot air balloon.

4. A ball is dropped vertically from a tower. If the vertical distance covered in the last second is equal to the distance covered in first three seconds, find the height of the tower.

5. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27K3    2. 27K4    3. 27K5    4. 27K6

 www.everythingscience.co.za     m.everythingscience.co.za

## Graphs of vertical projectile motion ESCJZ

We can describe vertical projectile motion through a series of graphs: position, velocity and acceleration versus time graphs. This isn't new, in Grade 10 you learnt about the graphs for describing rectilinear motion with constant acceleration. In the previous section we motivated for using the same equations of motion as in rectilinear motion. Therefore, everything you learnt about the graphs describing rectilinear motion is applicable when describing vertical projectile motion.

**IMPORTANT!**

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Now would be a good time to revise the section on graphs in rectilinear motion from Grade 10.

Remember that: $\vec{a} = \frac{\Delta \vec{v}}{\Delta t}$ and $\vec{v} = \frac{\Delta \vec{x}}{\Delta t}$. For the graphs of these quantities the slope and the area under a graph can tell us about changes in other quantities. As a reminder, here is a summary table, from Grade 10 rectilinear motion, about which information we can derive from the slope and the area of various graphs:

| Graph | Slope | Area |
|---|---|---|
| Displacement vs time | $\vec{v}$ | - |
| Velocity vs time | $\vec{a}$ | $\Delta\vec{x}$ |
| Acceleration vs time | - | $\vec{v}$ |
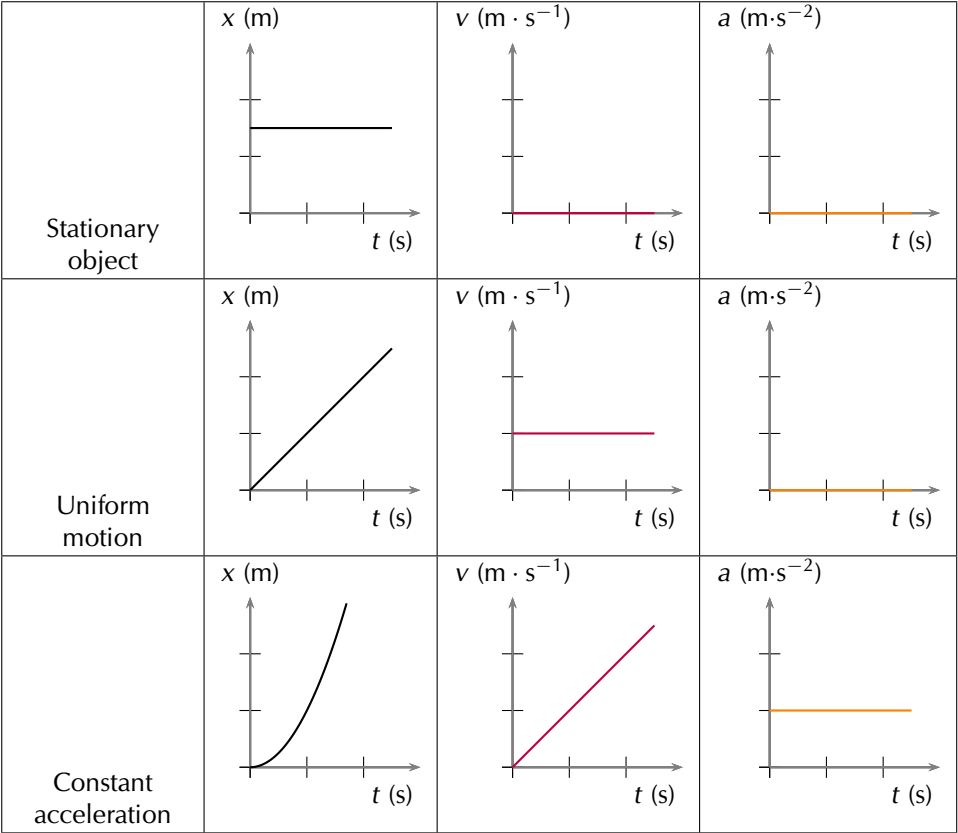
Figure 3.5: Position vs time, velocity vs time and acceleration vs time graphs.

---

The graphs are the graphical representations of the equations of motion. This means that if you have the graph for one of position, velocity or acceleration you should be able to write down the corresponding equation and vice versa.

The type of graphs is related to the equation of motion: position is a parabola, velocity is a straight line and acceleration is a constant. The characteristic features then depend on the sign convention and the specific values of the problem.

To illustrate the variation, we consider three separate cases: (1) the object has an initial velocity in the upward direction (opposite direction to $\vec{g}$), (2) the object falls from rest (no initial velocity), and (3) the object has an initial velocity in the downward direction (same direction as $\vec{g}$).

**Important:** the horizontal axis in these graphs is time, not space.

### Case 1: Initial velocity upwards

Consider an object undergoing the following motion:

1. at time $t = 0$ s the object has an initial position, $\vec{x}_i = 0$, and an initial upward velocity of magnitude $v_i$,
2. the object reaches a maximum height, $h_m$, above the ground,
3. the object then falls down to a final position, $\vec{x}_f$, with a final velocity $v_f$ downward at time $= t_f$.

The equation for position is given by: $\vec{x} = \vec{x}_i + \vec{v}_i t + \frac{1}{2}\vec{g}t^2$. We have to choose a positive direction as before.

We choose upwards as positive. The position versus time graph for the motion described is shown below:

**IMPORTANT!**

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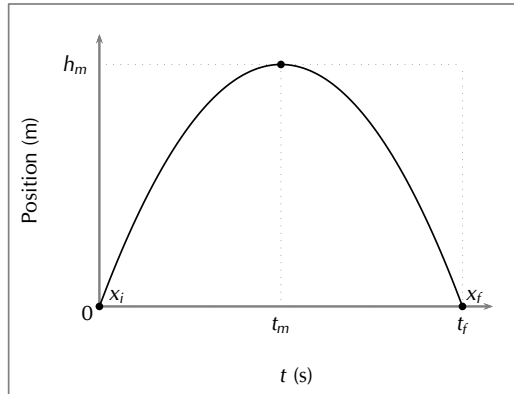
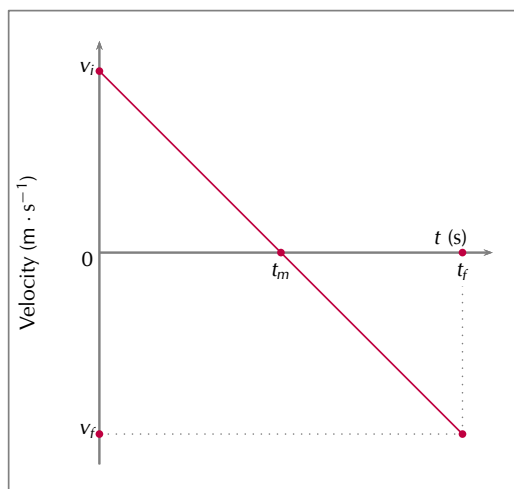
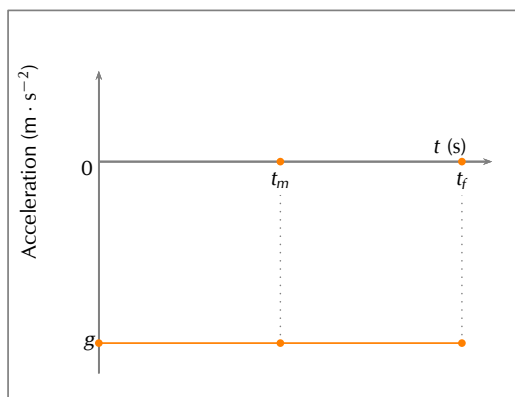
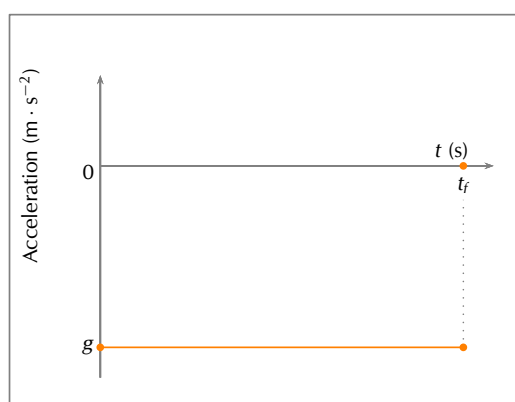

It is important to notice that we are plotting position versus time and the initial position, $\vec{x}_i$, is not necessarily zero. The position as a function of time will be given by $\vec{x}_f = \vec{x}_i + \vec{v}_i t + \frac{1}{2}\vec{g}t^2$. The initial position, $\vec{x}_i$, will shift the graph of $\vec{x}$ up or down by a constant value. Whether it is an upward or downward shift will depend on which direction was chosen as the positive direction. The magnitude of the shift will depend on the choice of origin for the coordinate system (frame of reference).

---

The second graph is a linear function showing the velocity as a function of time: $\vec{v}_f = \vec{v}_i + \vec{g}t$. Note that we chose upwards as our positive direction therefore the acceleration due to gravity will be negative. The slope (i.e. the coefficient of $t$) of the velocity versus time graph is the acceleration and the slope is negative which is consistent with our expectations after choosing upwards as the positive direction.

The final plot is a graph of acceleration versus time, and is constant because the magnitude and direction of the acceleration due to gravity are constant.

**Cases 2 & 3: Initial velocity zero or downwards**

We start by choosing a direction as the positive direction. We want to compare the graphs with the first case, so we will choose the same direction (upwards) to be the positive direction.
The one thing that remains the same is the acceleration, $\vec{g}$, due to gravity. Therefore:

If an object starts from rest (for example is dropped), then the initial velocity is zero. We know that there is constant acceleration and hence the graph of velocity versus time looks like this:

If the object starts with an initial velocity downwards the velocity graph looks like:

**IMPORTANT!**

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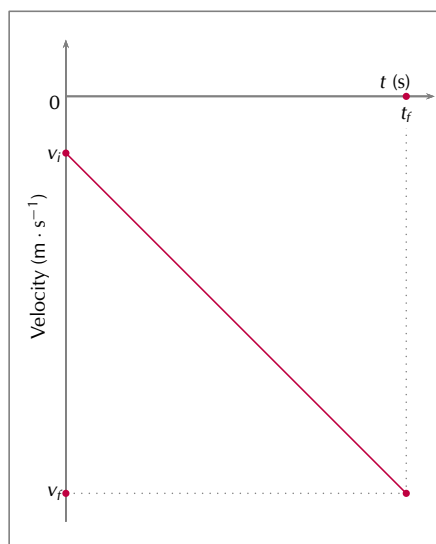
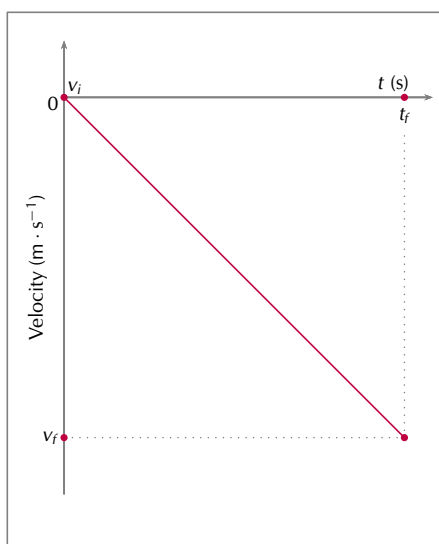

It is important to notice that the slope of all the velocity versus time graphs has the same magnitude. If the same direction is chosen as positive then the slope has the same magnitude AND the same sign (direction). The difference in these graphs is related to the initial velocity, $\vec{v}_i$. The magnitude of the slope of the graph is the magnitude of the acceleration.

---

For the case where the object falls from rest, the equation for position is $\vec{x} = \vec{x}_i + \underbrace{\vec{v}_i t}_{0} + \frac{1}{2}\vec{g}t^2$ and the graph of the position versus time looks as shown on the right.

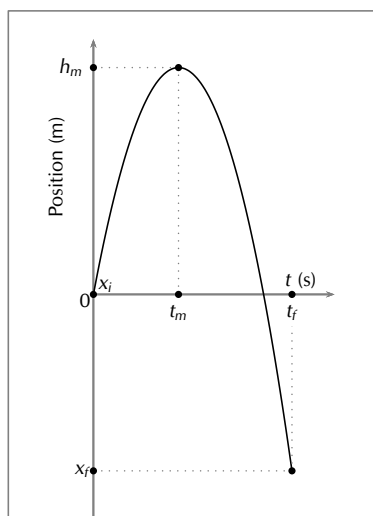
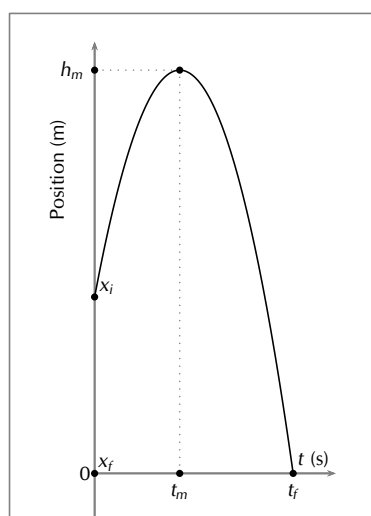
In this graph the initial velocity is zero:

For motion with an initial velocity in the negative direction, the graph of displacement versus time will be a narrower parabola as compared to the case where the object falls from rest.

In this graph the initial velocity is in the negative direction:

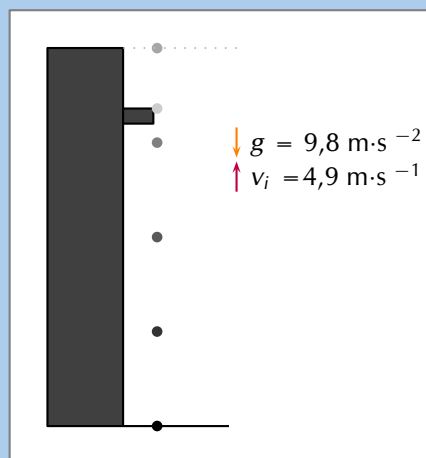
The primary difference in features between the cases we've looked at is that for Case 1, the position graph has a maximum positive displacement (it has a peak), while in Cases 2 and 3, where the initial velocity is negative, the displacement is always negative.

You may be wondering if the final position is always the same as the initial position, as we had for our Case 1 example. That is not necessarily true. If an object is thrown up from the edge of a cliff, the initial position of the object will be the height of the cliff but the final position will be at the base of the cliff.

If we choose the point from which the object is thrown as the origin of our coordinate system then the graph will look like this:

If we choose to centre our coordinate system at the base of the cliff then the graph will look like this, because the initial displacement is the height of the cliff:

Now let's look at some examples involving graphs of projectile motion.

**Worked example 4: Drawing graphs of projectile motion**

***QUESTION***

Stanley is standing on a balcony 20 m above the ground. Stanley tosses a rubber ball upwards with an initial velocity of 4,9 m·s $^{-1}$. The ball travels upwards to a maximum height, and then falls to the ground. Draw graphs of position vs time, velocity vs time and acceleration vs time. Choose upwards as the positive direction.

***SOLUTION***

**Step 1: Determine what is required**

We are required to draw graphs of:

1. $\vec{x}$ vs $t$
2. $\vec{v}$ vs $t$
3. $\vec{a}$ vs $t$

**Step 2: Determine how to approach the problem**

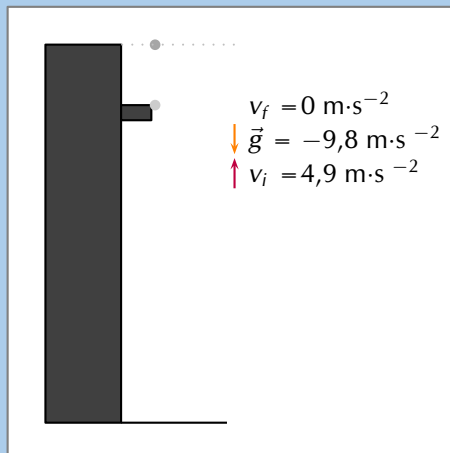
There are two parts to the motion of the ball:

1. ball travelling upwards from the building
2. ball falling to the ground

We examine each of these parts separately. To be able to draw the graphs, we need to determine the time taken and displacement for each of the motions.

**Step 3: Find the height and the time taken for the first motion**

For the first part of the motion we have:

- $\vec{v}_i = +4{,}9 \text{ m·s}^{-1}$
- $\vec{v}_f = 0 \text{ m·s}^{-1}$
- $\vec{g} = -9{,}8 \text{ m·s}^{-2}$

Therefore we can use $\vec{v}_f^2 = \vec{v}_i^2 + 2\vec{g}\Delta\vec{x}$ to solve for the height and $\vec{v}_f = \vec{v}_i + \vec{g}t$ to solve for the time.

$$\begin{aligned} \vec{v}_f^2 &= \vec{v}_i^2 + 2\vec{g}\Delta\vec{x} \\ (0)^2 &= (4{,}9)^2 + 2 \times (-9{,}8) \times \Delta\vec{x} \\ 19{,}6\Delta x &= (4{,}9)^2 \\ \Delta\vec{x} &= +1{,}225 \text{ m} \\ h &= \Delta x = 1{,}225 \text{ m} \end{aligned}$$

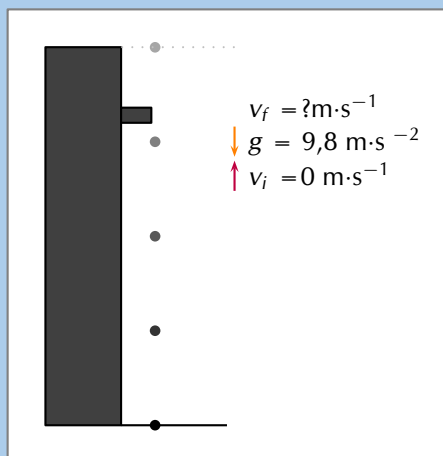
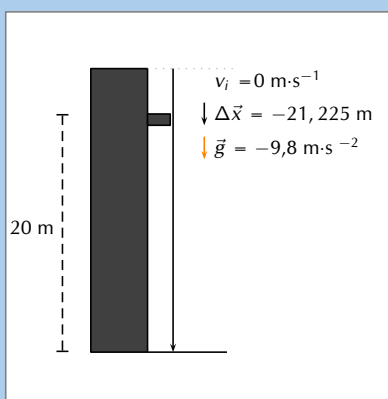
$$\begin{aligned} \vec{v}_f &= \vec{v}_i + \vec{g}t \\ 0 &= 4{,}9 + (-9{,}8) \times t \\ 9{,}8t &= 4{,}9 \\ t &= 0{,}5 \text{ s} \end{aligned}$$

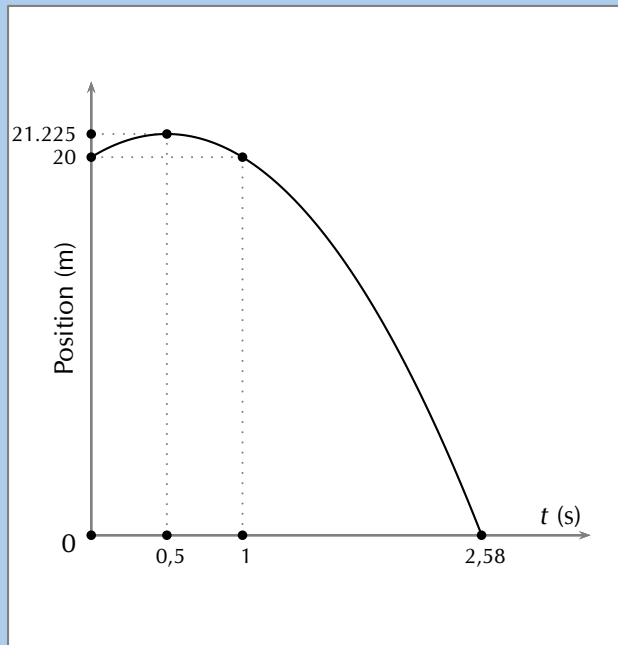
**Step 4: Find the height and the time taken for the second motion**

For the second part of the motion we have:

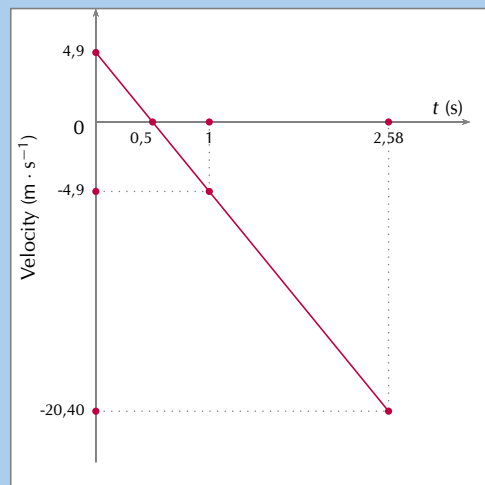
- $\vec{v}_i = 0 \text{ m·s}^{-1}$
- $\Delta\vec{x} = -(20 + 1{,}225) \text{ m}$
- $\vec{g} = -9{,}8 \text{ m·s}^{-2}$

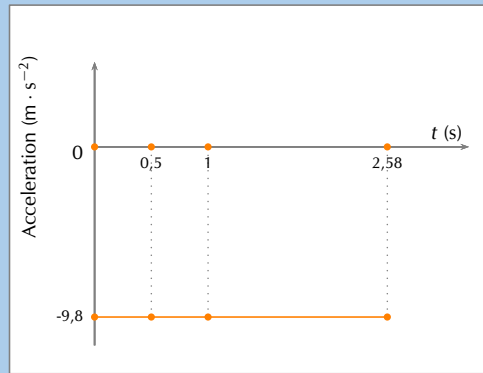
$v_f = ?\text{m·s}^{-1}$
$g = 9{,}8 \text{ m·s}^{-2}$
$v_i = 0 \text{ m·s}^{-1}$

Therefore we can use $\Delta\vec{x} = \vec{v}_i t + \frac{1}{2}\vec{g}t^2$ to solve for the time.

$$\begin{aligned} \Delta\vec{x} &= \vec{v}_i t + \frac{1}{2}\vec{g}t^2 \\ -(20 + 1{,}225) &= (0) \times t + \frac{1}{2} \times (-9{,}8) \times t^2 \\ -21{,}225 &= 0 - 4{,}9t^2 \\ t^2 &= 4{,}33163... \\ t &= 2{,}08125 \text{ s} \end{aligned}$$

**Step 5: Graph of position vs time**

The ball starts from a position of 20 m (at t = 0 s) from the ground and moves upwards until it reaches 20+1,225 m (at $t$ = 0,5 s). It then falls back to 20 m (at $t$ = 0,5 + 0,5 = 1,0s) and then falls to the ground, $\Delta\vec{x}$ = 0 m (at $t$ = 0,5 + 2,08 = 2,58 s).

**Step 6: Graph of velocity vs time**

The ball starts off with a velocity of +4,9 m·s $^{-1}$ at t = 0 s, it then reaches a velocity of 0 m·s $^{-1}$ at t = 0,5 s. It stops and falls back to the Earth. At t = 1,0 s (i.e. after a further 0,5 s) it has a velocity of −4,9 m·s $^{-1}$. This is the same as the initial upwards velocity but it is downwards. It carries on at constant acceleration until $t$ = 2,58 s. In other words, the velocity graph will be a straight line. The final velocity of the ball can be calculated as follows:

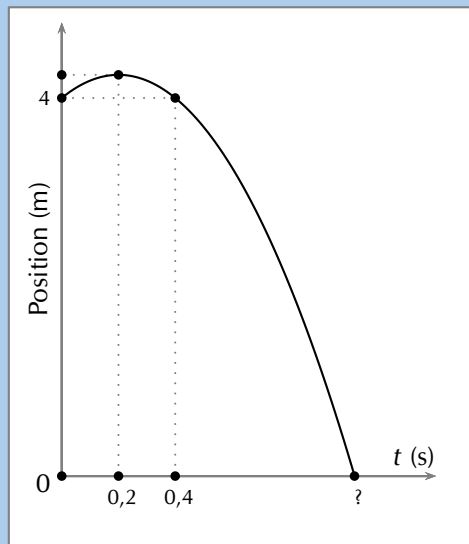
$$\begin{aligned}\vec{v}_f &= \vec{v}_i + \vec{g}t \\ &= 0 + (-9,8)(2,08...) \\ &= -20,396...\ \text{m}\cdot\text{s}^{-1}\end{aligned}$$

**Step 7: Graph of $a$ vs $t$**

We chose upwards to be positive. The acceleration of the ball is downward, $\vec{g}$ = 9,8 m·s $^{-2}$ downwards. Because the acceleration is constant throughout the motion, the graph looks like this:

**Worked example 5: Analysing graphs of projectile motion**

***QUESTION***

The graph below (not drawn to scale) shows the motion of a tennis ball that was thrown vertically upwards from an open window some distance from the ground. It takes the ball 0,2 sto reach its highest point before falling back to the ground.

Study the graph given and calculate:

1. how high the window is above the ground.
2. the time it takes the ball to reach the maximum height.
3. the initial velocity of the ball.
4. the maximum height that the ball reaches.
5. the final velocity of the ball when it reaches the ground.

***SOLUTION***

**Step 1: Find the height of the window**

The initial position of the ball will tell us how high the window is. From the y-axis on the graph we can see that the ball is 4 m from the ground.

The window is therefore 4 m above the ground.

**Step 2: Find the time taken to reach the maximum height**

The maximum height is where the position vs time graph reaches its maximum position. This is when t = 0,2 s.

It takes the ball 0,2 s to reach the maximum height.

**Step 3: Find the initial velocity ($\vec{v}_i$) of the ball**

To find the initial velocity we only look at the first part of the motion of the ball. That is from when the ball is released until it reaches its maximum height. We have the following for this:

In this case, let's choose upwards as positive.

$$t = 0{,}2 \text{ s}$$
$$\vec{g} = 9{,}8 \text{ m·s}^{-2}$$
$$\vec{v}_f = 0 \text{ m} \cdot \text{s}^{-1} \text{ (because the ball stops)}$$

To calculate the initial velocity of the ball ($\vec{v}_i$), we use:

$$\vec{v}_f = \vec{v}_i + \vec{g}t$$
$$0 = \vec{v}_i + (-9{,}8)(0{,}2)$$
$$v_i = 1{,}96 \text{ m} \cdot \text{s}^{-1}$$

The initial velocity of the ball is 1,96 m·s $^{-1}$ upwards.

**Step 4: Find the maximum height of the ball**

To find the maximum height we look at the initial motion of the ball.

We have the following:

$$t = 0{,}2 \text{ s}$$
$$\vec{g} = 9{,}8 \text{ m·s}^{-2}$$
$$\vec{v}_f = 0 \text{ m} \cdot \text{s}^{-1} \text{ (because the ball stops)}$$
$$\vec{v}_i = +1{,}96 \text{ m} \cdot \text{s}^{-1} \text{(calculated above)}$$

To calculate the displacement from the window to the maximum height ($\Delta x$) we use:

$$\Delta\vec{x} = \vec{v}_i t + \frac{1}{2}\vec{g}t^2$$
$$\Delta\vec{x} = (1{,}96)(0{,}2) + \frac{1}{2}(-9{,}8)(0{,}2)^2$$
$$\Delta\vec{x} = 0{,}196 \text{ m}$$

The maximum height of the ball is (4 + 0,196) = 4,196m above the ground.

**Step 5: Find the final velocity ($\vec{v}_f$) of the ball**

To find the final velocity of the ball we look at the second part of the motion. For this we have:

$$\Delta\vec{x} = -4{,}196 \text{ m (because upwards is positive)}$$
$$\vec{g} = -9{,}8 \text{ m·s}^{-2}$$
$$\vec{v}_i = 0 \text{ m} \cdot \text{s}^{-1}$$

We can use $\vec{v}_f^2 = \vec{v}_i^2 + 2\vec{g}\Delta\vec{x}$ to calculate the final velocity of the ball.

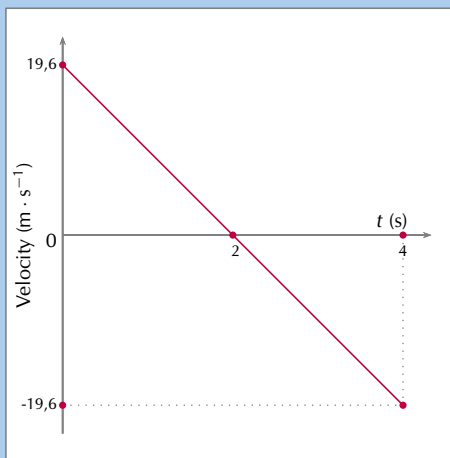
$$\vec{v}_f^2 = \vec{v}_i^2 + 2\vec{g}\Delta\vec{x}$$
$$\vec{v}_f^2 = (0)^2 + 2(-9{,}8)(-4{,}196)$$
$$\vec{v}_f^2 = 82{,}2416$$
$$\vec{v}_f = 9{,}0687 \text{ m·s}^{-1} \text{ downwards}$$

The final velocity of the ball is 9,07 m·s $^{-1}$ *downwards*.

**Worked example 6: Describing projectile motion**

***QUESTION***

A cricketer hits a cricket ball from the ground and the following graph of velocity vs time was drawn. Upwards was taken as positive. Study the graph and follow the instructions below:

1. Describe the motion of the ball according to the graph.
2. Draw a sketch graph of the corresponding position-time graph. Label the axes.
3. Draw a sketch graph of the corresponding acceleration-time graph. Label the axes.

***SOLUTION***

**Step 1: Describe the motion of the ball**

We need to study the velocity-time graph to answer this question. We will break the motion of the ball up into two time zones: $t = 0$ s to $t = 2$ s and $t = 2$ s to $t = 4$ s.

From $t = 0$ s to $t = 2$ s the following happens:

The ball starts to move at an initial velocity of 19,6 m·s $^{-1}$ and decreases its velocity to 0 m·s $^{-1}$ at $t = 2$ s. At $t = 2$ s the velocity of the ball is 0 m·s $^{-1}$ and therefore it stops.

From $t = 2$ s to $t = 4$ s the following happens:

The ball moves from a velocity of 0 m·s $^{-1}$ to 19,6 m·s $^{-1}$ in the opposite direction to the original motion.

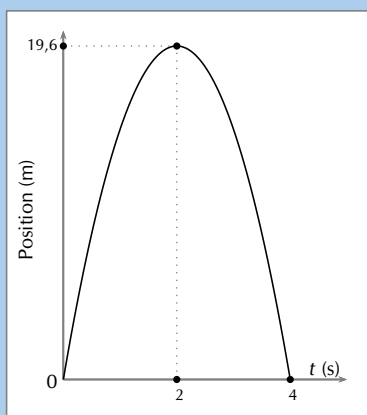
If we assume that the ball is hit straight up in the air (and we take upwards as positive), it reaches its maximum height at $t = 2$ s, stops, and falls back to the Earth to reach the ground at $t = 4$ s.

**Step 2: Draw the position-time graph**

To draw this graph, we need to determine the displacements at $t = 2$ s and $t = 4$ s.

At $t = 2$ s:
The displacement is equal to the area under the graph:
Area under graph = Area of triangle
Area $= \frac{1}{2}bh$
Area $= \frac{1}{2} \times 2 \times 19{,}6$
Position = 19,6 m

At $t = 4$ s:
The displacement is equal to the area under the whole graph (top and bottom). Remember that an area under the time line must be subtracted:
Area under graph = Area of triangle 1 + Area of triangle 2
Area $= \frac{1}{2}bh + \frac{1}{2}bh$
Area $= \left(\frac{1}{2} \times 2 \times 19{,}6\right) + \left(\frac{1}{2} \times 2 \times (-19{,}6)\right)$
Area $= 19{,}6 - 19{,}6$
Displacement = 0 m

The position vs time graph for motion at constant acceleration is a curve. The graph will look like this:

**Step 3: Draw the acceleration versus time graph**

To draw the acceleration vs time graph, we need to know what the acceleration is. The velocity versus time graph is a straight line which means that the acceleration is constant. The gradient of the line will give the acceleration.

The line has a negative slope (goes down towards the left) which means that the acceleration has a negative value.

Calculate the gradient of the line:

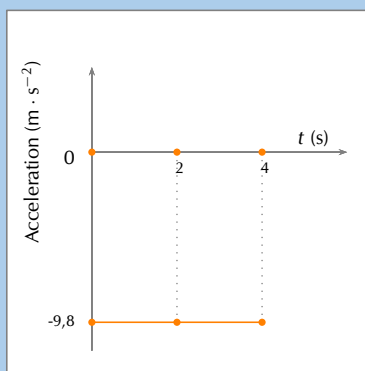
$$\text{gradient} = \frac{\Delta \vec{v}}{\Delta t}$$

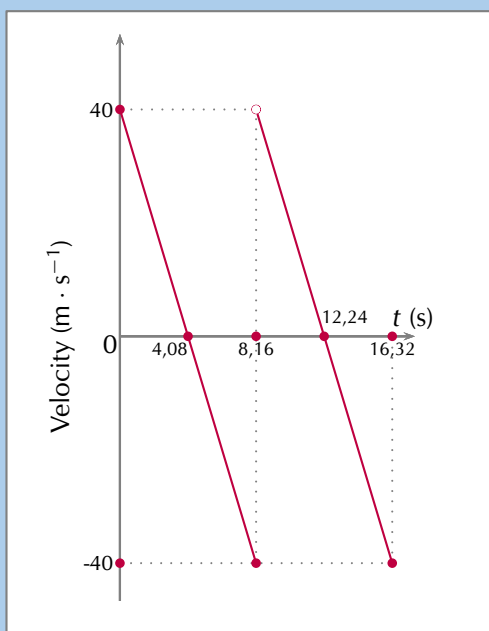
$$\text{gradient} = \frac{0 - 19{,}6}{2 - 0}$$

$$\text{gradient} = \frac{-19{,}6}{2}$$

$$\text{gradient} = -9{,}8$$

Therefore the acceleration = 9,8 m·s $^{-2}$ downwards.

**Worked example 7: Interpreting velocity graphs**

***QUESTION***

Describe the motion corresponding to the following graph and plot the position vs time and acceleration vs time assuming the initial position is 0:

***SOLUTION***

**Step 1: Determine what is required**

The velocity vs time graph corresponding to the motion of an object is given, using the graph we need to describe the actual motion. Notice that the graph has discontinuities, this naturally breaks the graph into phases. We should process each phase separately and then try to infer (figure out) what probably happened to change from one phase to the next.

The first thing that you normally do in a vertical projectile motion problem is choose a positive direction. In this case you can't do that because it has already been decided. We need to use the information given to figure out which direction was chosen as positive.

**Step 2: Determine the direction chosen as positive**

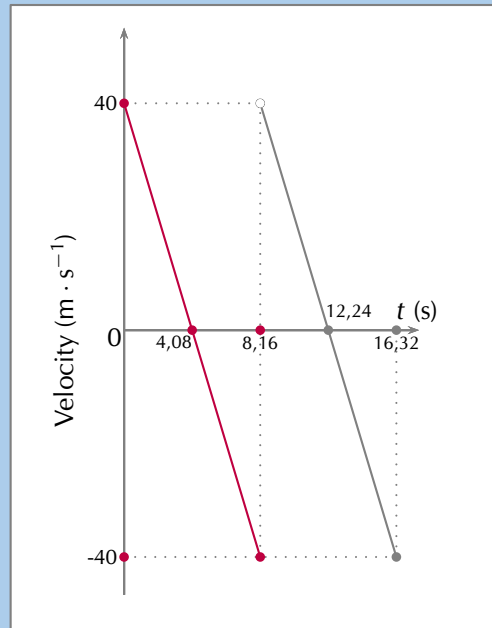
We are given a velocity vs time graph. We know that the slope of the velocity time graph is the acceleration and we know that in these problems we are only dealing with gravitational acceleration. We can use what we know about gravitational acceleration and the slope of the graph to determine which direction was chosen as positive.

Gravitational acceleration is always directed towards the centre of the Earth. If we choose:

- **upwards as the positive** direction then the slope of the velocity vs time graph will be negative
- **downwards as the positive** direction then the slope of the velocity vs time graph will be positive

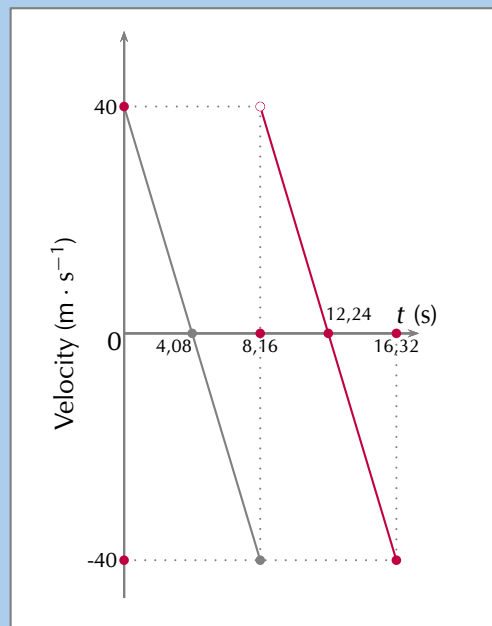
In this problem the slope of the velocity vs time graph is negative and so we know that upwards was chosen as the positive direction.

**Step 3: First phase**

In the plot below we highlight only the first phase of interest.

The initial velocity is positive and then decreases linearly, passes through zero and reaches the same magnitude in the negative direction. The positive starting value means the object was going upwards, the linear decreases means a constant acceleration in the negative direction, passing through zero means that the object reaches a maximum height before beginning to fall in the negative direction. The fact that the magnitude of the initial and final velocities is the same means that there is time symmetry.

This is just the plot of an object being thrown/shot/projected upwards, peaking and falling back to the same level as it was thrown from.

**Step 4: Second phase**

In the plot below we highlight only the second phase.

Just as in the first phase, the initial velocity is positive and then decreases linearly, passes through zero and reaches the same magnitude in the negative direction. The positive starting value means the object was going upwards, the linear decreases means a constant acceleration in the negative direction, passing through zero means that the object reaches a maximum height before beginning to fall in the negative direction. The fact that the magnitude of the initial and final velocities is the same means that there is time symmetry.

This is just the plot of an object being thrown upwards, peaking and falling back to the same level as it was thrown from.

**Step 5: Combining phases**

We know that the two phases look the same, the object starts off moving upwards, peaks, falls down to the initial position and then repeats the process. This could be a description of a ball bouncing as an example.

**Step 6: Position vs time**

To draw an accurate position graph we know that we are dealing with the Case 1 situation from earlier. We need to determine the height that the object rises to and then we can plot the position vs time. We know the timing information from the velocity vs time plot.

We can verify that the acceleration is in fact from gravity by using $\vec{v}_f = \vec{v}_i + \vec{g}t$:

$$\begin{aligned} \vec{v}_f &= \vec{v}_i + \vec{g}t \\ (-40) &= (40) + \vec{g}(8,16) \\ (-80) &= \vec{g}(8,16) \\ \vec{g} &= \frac{-80}{8,16} \\ \vec{g} &= -9,8 \text{ m·s}^{-2} \end{aligned}$$

We can work out the height using the equation for displacement:

$$\begin{aligned} \vec{v}_f^2 &= \vec{v}_i^2 + 2\vec{g}\Delta\vec{x} \\ 0 &= (40)^2 + 2(-9,8)\Delta\vec{x} \\ \Delta\vec{x} &= \frac{-(40)^2}{2(-8,16)} \\ \Delta\vec{x} &= 81,63 \text{ m} \end{aligned}$$

So we can now draw the displacement vs time plot:

**Step 7: Acceleration vs time**

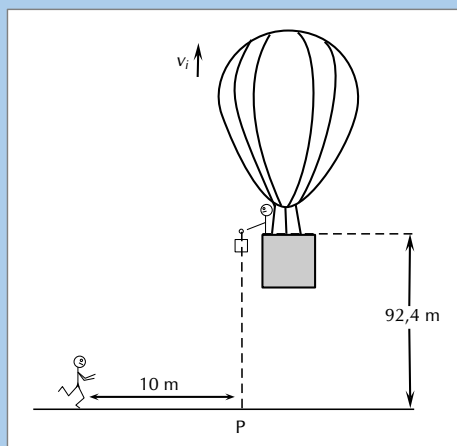
The acceleration is due to gravity except at one point, when the object bounces.

At that point the acceleration must be some other, very large, value in the positive direction but we don't have enough information to determine what the value must be.

We explicitly note that at that point the acceleration is NOT -9,8 m·s $^{-2}$.

**Worked example 8: Hot air balloon [NSC 2011 Paper 1]**

***QUESTION***

A hot-air balloon is moving vertically upwards at a constant speed. A camera is accidentally dropped from the balloon at a height of 92,4 m as shown in the diagram below. The camera strikes the ground after 6 s. Ignore the effects of friction.

1. At the instant the camera is dropped, it moves upwards. Give a reason for this observation. (1 mark)
2. Calculate the speed $v_i$ at which the balloon is rising when the camera is dropped. (4 marks)
3. Draw a sketch graph of velocity versus time for the entire motion of the camera. Indicate the following on the graph:

   - Initial velocity
   - Time at which it reaches the ground (4 marks)

4. If a jogger, 10 m away from point **P** as shown in the above diagram and running at a constant speed of 2 $\text{m}\cdot\text{s}^{-1}$, sees the camera at the same instant it starts falling from the balloon, will he be able to catch the camera before it strikes the ground? Use a calculation to show how you arrived at the answer. (5 marks)

**[TOTAL: 14 marks]**

***SOLUTION***

**Question 1** The initial velocity / speed of the camera is the same (as that of the balloon). (1 marks)

**Question 2**

**Taking downwards as the positive direction:**

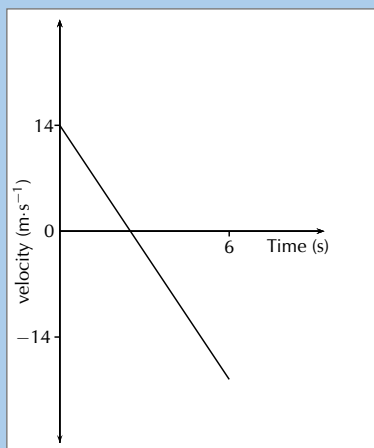
$$\begin{aligned}\Delta y &= v_i\Delta t + \frac{1}{2}a\Delta t^2\\ \therefore 92{,}4 &= v_i(6) + \frac{1}{2}(9{,}8)(6)^2\\ \therefore v_i &= -14\ \text{m}\cdot\text{s}^{-1}\\ \therefore v_i &= 14\ \text{m}\cdot\text{s}^{-1}\end{aligned}$$

**Taking downwards as the negative direction:**

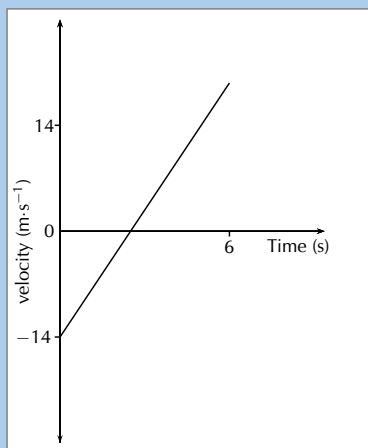
$$\begin{aligned}\Delta y &= v_i\Delta t + \frac{1}{2}a\Delta t^2\\ \therefore -92{,}4 &= v_i(6) + \frac{1}{2}(-9{,}8)(6)^2\\ \therefore v_i &= 14\ \text{m}\cdot\text{s}^{-1}\end{aligned}$$

(4 marks)

**Question 3**

**Taking downwards as the positive direction:**

**Criteria for graph:**

- Correct shape as shown. (Straight line with gradient.)
- Graph starts at $v = 14\ \text{m}\cdot\text{s}^{-1}$ / $v_i$ at $t = 0$ s.
- Graph extends below $t$ axis until $t = 6$ s.
- Section of graph below $t$ axis is longer than section above $t$ axis.

**Taking downwards as the negative direction:**

**Criteria for graph:**

- Correct shape as shown. (Straight line with gradient.)
- Graph starts at $v = -14\ \text{m}\cdot\text{s}^{-1}$ / $v_i$ at $t = 0$ s.
- Graph extends above $t$ axis until $t = 6$ s.
- Section of graph above $t$ axis is longer than section below $t$ axis.

(4 marks)

**Question 4**

**Option 1:**

$$\Delta x = v\Delta t$$
$$\therefore 10 = (2)\Delta t$$
$$\therefore \Delta t = 5\ \text{s}$$

Yes, he will catch the camera since the time is less than 6 s.

**Option 2:**

$$\Delta x = v\Delta t$$
$$\therefore = (2)(6)$$
$$\therefore = 12\ \text{m}$$

Yes, he will catch the camera since the distance covered is greater than 10 m.

**Option 3:**

$$\Delta x = v_i\Delta t + \frac{1}{2}a\Delta t^2$$
$$\therefore 10 = (2)\Delta t + \frac{1}{2}(0)\Delta t^2$$
$$\therefore \Delta t = 5\ \text{t}$$

Yes, he will catch the camera since the time is less than 6 s.

**Option 4:**

$$\Delta x = \left(\frac{v_i + v_f}{2}\right)\Delta t$$
$$\therefore 10 = \left(\frac{2 + 2}{2}\right)\Delta t$$
$$\therefore \Delta t = 5\ \text{t}$$

Yes, he will catch the camera since the time is less than 6 s.

**Option 5:**

$$\Delta x = \left(\frac{v_i + v_f}{2}\right)\Delta t$$
$$= \left(\frac{2 + 2}{2}\right)(6)$$
$$\therefore \Delta x = 12\ \text{m}$$

Yes, he will catch the camera since the distance covered is greater than 10 m.
(5 marks)

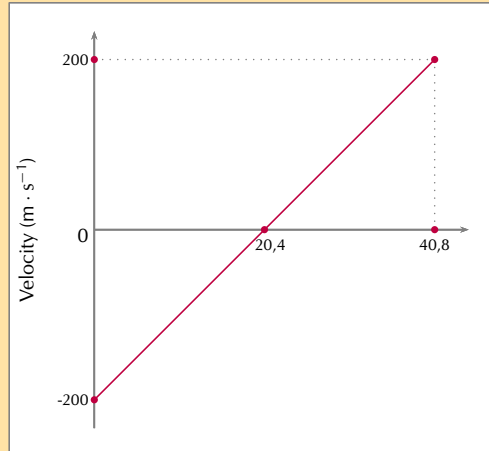
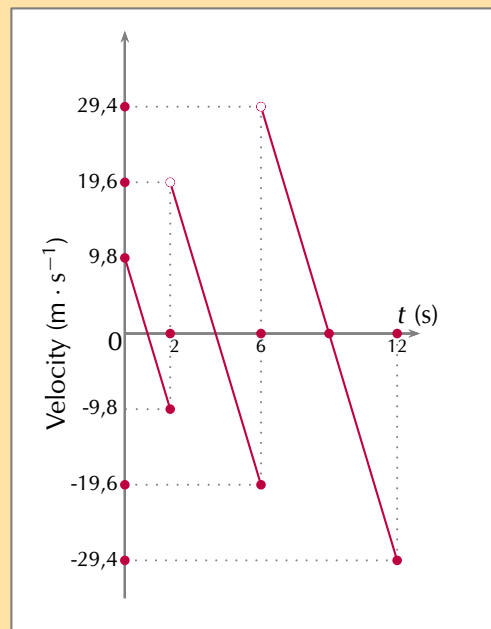
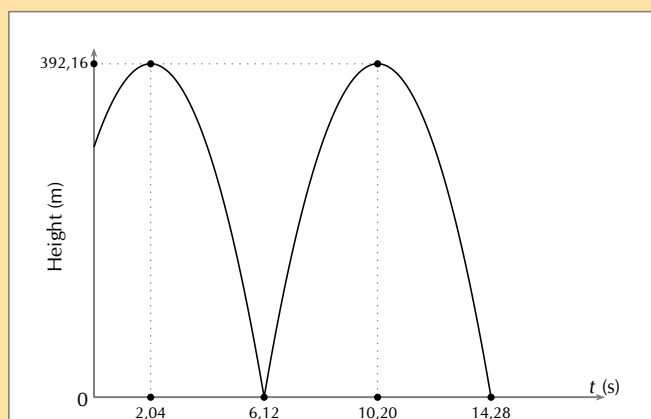
**[TOTAL: 14 marks]**

## Exercise 3 – 2: Graphs of vertical projectile motion

1. Amanda throws a tennis ball from a height of 1,5 m straight up into the air and then lets it fall to the ground. Draw graphs of $x$ vs $t$; $v$ vs $t$ and $a$ vs $t$ for the motion of the ball. The initial velocity of the tennis ball is $2\text{m} \cdot \text{s}^{-1}$. Choose upwards as positive.
2. A bullet is shot straight upwards from a gun.

   The following graph is drawn. Downwards was chosen as positive

   a) Describe the motion of the bullet.
   b) Draw a displacement - time graph.
   c) Draw an acceleration - time graph.
3. Describe the motion resulting from the velocity vs time graph shown below, assuming an initial height of 0 m, and draw a displacement vs time graph and an acceleration vs time graph:

   
   
4. What is the initial height? Draw a velocity vs time graph and an acceleration vs time graph that would result in this displacement vs time graph:

5. A ball that always bounces off the floor with the same magnitude of the velocity as it hit the floor is dropped from 3 m above a stack of 4 crates. Each crate is 30 cm high. After the ball bounces off a crate it is quickly removed so that the next time the ball bounces it bounces off the next crate in the pile. This is repeated until all the crates have been removed. Draw the following graphs for the situation:
   - Displacement vs time
   - Velocity vs time
   - Acceleration vs time
6. A ball is dropped from 4 m above a cushioned mat. Each time the ball bounces the magnitude of the velocity in the upwards direction is half the magnitude of the velocity with which it hit the floor. The ball is allowed to bounce 3 times, draw the following graphs for the situation and the equation describing each section of the graph:
   - Displacement vs time
   - Velocity vs time
   - Acceleration vs time
7. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27K7 2. 27K8 3. 27K9 4. 27KB 5. 27KC 6. 27KD

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## 3.3 Chapter summary ESCK2

See presentation: 27KF at www.everythingscience.co.za

- Projectiles are objects that move through the air. In vertical projectile motion we deal with objects that fall under the influence of gravity and only vertically.
- Objects that move up and down (vertical projectiles) on the Earth accelerate with a constant acceleration $\vec{g}$ which is approximately equal to 9,8 m·s $^{-2}$directed

downwards towards the centre of the earth.

- The time it takes an object to rise to its maximum height, is the same as the time it will take to fall back to its initial height. The magnitude of the velocity will also be the same but the direction will be reversed. This is known as time symmetry and is a consequence of uniform gravitational acceleration.
- The equations of motion can be used to solve vertical projectile problems.

$$\vec{v}_f = \vec{v}_i + \vec{g}t$$

$$\Delta\vec{x} = \frac{(\vec{v}_i + \vec{v}_f)}{2}t$$

$$\Delta\vec{x} = \vec{v}_i t + \frac{1}{2}\vec{g}t^2$$

$$\vec{v}_f^2 = \vec{v}_i^2 + 2\vec{g}\Delta\vec{x}$$

- Graphs for vertical projectile motion are similar to graphs for motion at constant acceleration.

| **Physical Quantities** | | | |
|---|---|---|---|
| **Quantity** | **Vector** | **Unit name** | **Unit symbol** |
| Position ($x$) | - | metre | m |
| Displacement ($\Delta\vec{x}$) | ✓ | metre | m |
| Instantaneous velocity ($\vec{v}$) | ✓ | metre per second | $m{\cdot}s^{-1}$ |
| Instantaneous speed ($v$) | - | metre per second | $m{\cdot}s^{-1}$ |
| Instantaneous acceleration ($\vec{a}$) | ✓ | metre per second per second | $m{\cdot}s^{-2}$ |
| Magnitude of acceleration ($a$) | - | metre per second per second | $m{\cdot}s^{-2}$ |

Table 3.1: Units used in **vertical projectile motion**.

**Exercise 3 – 3:**

1. [SC 2001/11 HG1] A bullet fired vertically upwards reaches a maximum height and falls back to the ground.
   Which **one** of the following statements is **true** with reference to the acceleration of the bullet during its motion, if air resistance is ignored? The acceleration:
   a) is always downwards
   b) is first upwards and then downwards
   c) is first downwards and then upwards
   d) decreases first and then increases
2. [IEB 2002/11 HG1] Two balls, P and Q, are simultaneously thrown into the air from the same height above the ground. P is thrown vertically upwards and Q vertically downwards with the same initial speed. Which of the following is true of both balls just before they hit the ground? (Ignore any air resistance. Take downwards as the positive direction.)

| | **Velocity** | **Acceleration** |
|---|---|---|
| A | The same | The same |
| B | P has a greater velocity than Q | P has a negative acceleration; Q has a positive acceleration |
| C | P has a greater velocity than Q | The same |
| D | The same | P has a negative acceleration; Q has a positive acceleration |

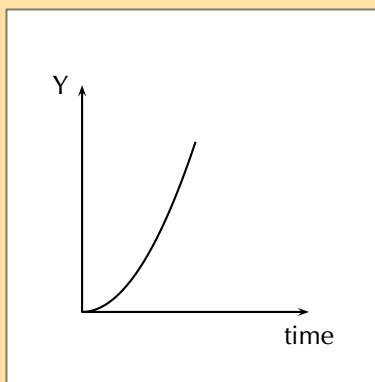
3. [SC 2003/11] A ball X of mass m is projected vertically upwards at a speed $u_x$ from a bridge 20 mhigh. A ball Y of mass $2m$ is projected vertically downwards from the same bridge at a speed of $u_y$. The two balls reach the water at the same speed. Air friction can be ignored.

   Which of the following is true with reference to the speeds with which the balls are projected?

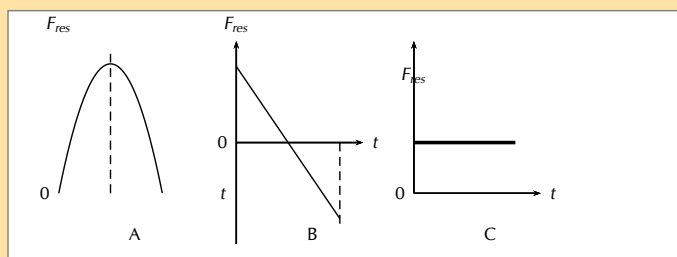
   a) $u_x = \frac{1}{2}u_y$
   b) $u_x = u_y$
   c) $u_x = 2u_y$
   d) $u_x = 4u_y$

4. [SC 2002/03 HG1]

   A stone falls freely from rest from a certain height. Which one of the following quantities could be represented on the y-axis of the graph below?

   a) velocity
   b) acceleration
   c) momentum
   d) displacement

5. A stone is thrown vertically upwards and it returns to the ground. If friction is ignored, its acceleration as it reaches the highest point of its motion is

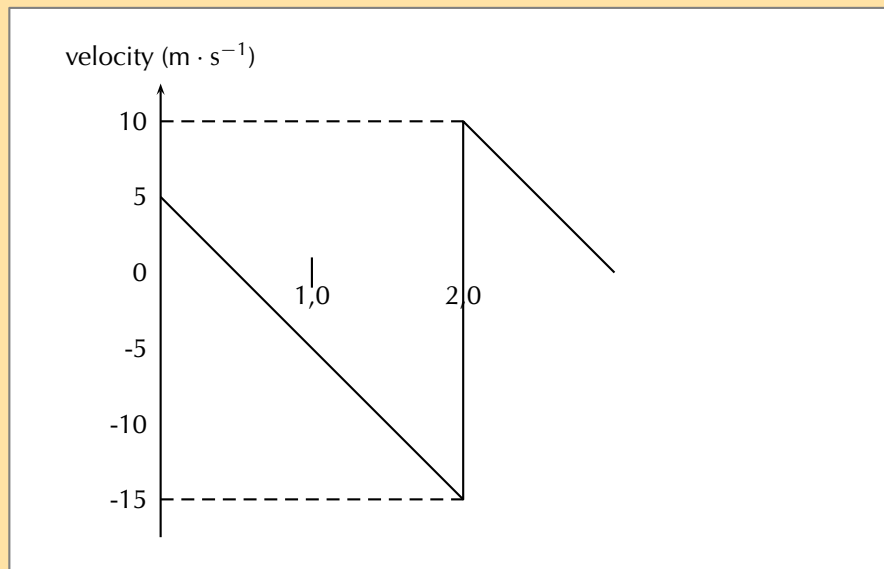
   a) greater than just after it left the throwers hand.
   b) less than just before it hits the ground.
   c) the same as when it left the throwers hand.
   d) less than it will be when it strikes the ground.

6. [IEB 2004/11 HG1] A stone is thrown vertically up into the air. Which of the following graphs best shows the resultant force exerted on the stone against time while it is in the air? (Air resistance is negligible.)

7. What is the velocity of a ball just as it hits the ground if it is thrown upward at 10 m·s $^{-1}$ from a height 5 meters above the ground?

8. [IEB 2002/11 HG1 - Bouncing Ball]

   A ball bounces vertically on a hard surface after being thrown vertically up into the air by a boy standing on the ledge of a building.

   Just before the ball hits the ground for the first time, it has a velocity of magnitude 15 m·s $^{-1}$. Immediately, after bouncing, it has a velocity of magnitude 10 m·s $^{-1}$.

The graph below shows the velocity of the ball as a function of time from the moment it is thrown upwards into the air until it reaches its maximum height after bouncing once.

a) At what velocity does the boy throw the ball into the air?

b) What can be determined by calculating the gradient of the graph during the first two seconds?

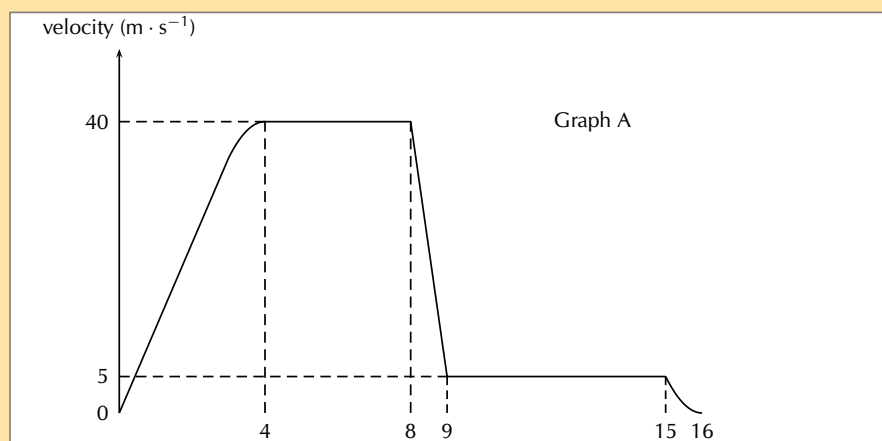
c) Determine the gradient of the graph over the first two seconds. State its units.

d) How far below the boy's hand does the ball hit the ground?

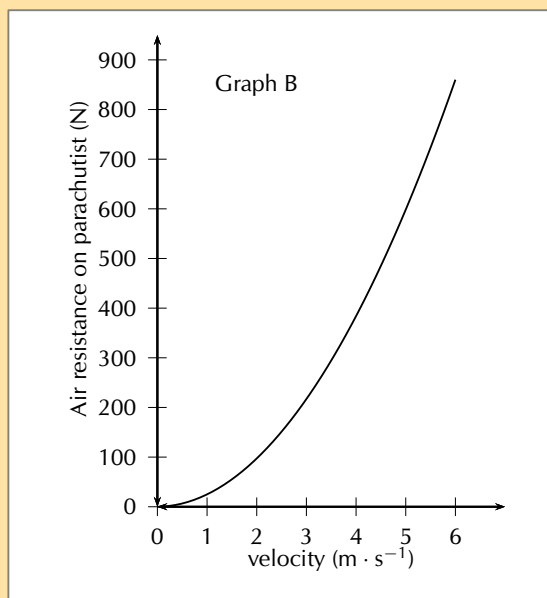
e) Use an equation of motion to calculate how long it takes, from the time the ball was thrown, for the ball to reach its maximum height after bouncing.

f) What is the position of the ball, measured from the boy's hand, when it reaches its maximum height after bouncing?

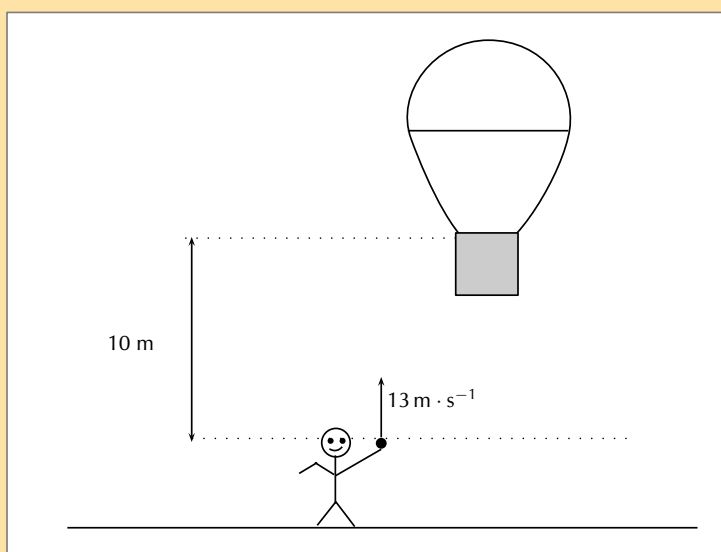
9. [IEB 2001/11 HG1] - **Free Falling?**

   A parachutist steps out of an aircraft, flying high above the ground. She falls for the first 8 seconds before opening her parachute. A graph of her velocity is shown in Graph A below.

a) Use the information from the graph to calculate an approximate height of the aircraft when she stepped out of it (to the nearest 10 m).

b) What is the magnitude of her velocity during her descent with the parachute fully open?

The air resistance acting on the parachute is related to the speed at which the parachutist descends. Graph B shows the relationship between air resistance and velocity of the parachutist descending with the parachute open.

c) Use Graph B to find the magnitude of the air resistance on her parachute when she was descending with the parachute open.

d) Assume that the mass of the parachute is negligible. Calculate the mass of the parachutist showing your reasoning clearly.

10. Niko, in the basket of a hot-air balloon, is stationary at a height of 10 m above the level from where his friend, Bongi, will throw a ball. Bongi intends throwing the ball upwards and Niko, in the basket, needs to **descend** (move downwards) to catch the ball at its maximum height.

Bongi throws the ball upwards with a velocity of 13 $m\cdot s^{-1}$. Niko starts his descent at the same instant the ball is thrown upwards, by letting air escape from the balloon, causing it to accelerate downwards. Ignore the effect of air friction on the ball.

a) Calculate the maximum height reached by the ball.

b) Calculate the magnitude of the minimum average acceleration the balloon must have in order for Niko to catch the ball at its maximum height.

11. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27KG 2. 27KH 3. 27KJ 4. 27KK 5. 27KM 6. 27KN
7. 27KP 8. 27KQ 9. 27KR 10. 27KS

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CHAPTER

# Organic molecules

## 4.1 What are organic molecules? ESCK3

**Organic chemistry** is the branch of chemistry that deals with **organic molecules**. An organic molecule is one which contains **carbon**, although not all compounds that contain carbon are organic molecules. Noticeable exceptions are carbon monoxide (CO), carbon dioxide ($CO_2$), carbonates (e.g. calcium carbonate), carbides (e.g. calcium carbide) and cyanides (e.g. sodium cyanide). Pure carbon compounds such as diamond and graphite are also **not** organic compounds. Organic molecules can range in size from simple molecules to complex structures containing thousands of atoms!

Although carbon is present in all organic compounds, other elements such as hydrogen (H), oxygen (O), nitrogen (N), sulfur (S) and phosphorus (P) are also common in these molecules.

**DEFINITION:** *Organic molecule*

An organic molecule is a molecule that contains carbon atoms (generally bonded to other carbon atoms as well as hydrogen atoms).

Organic compounds are very important in daily life and they range from simple to extremely complex (Figure 4.1).

Organic molecules make up a big part of our own bodies, they are in the food we eat and in the clothes we wear. Organic compounds are also used to make products such as medicines, plastics, washing powders, dyes, along with a long list of other items. There are millions organic compounds found in nature, as well as millions of synthetic (man-made) organic compounds.

Figure 4.1: A simple organic molecule, propane, can be used in a gas lamp (left). The complex organic molecule DNA carries the genetic code of a person and can be used to identify them.

## 4.2 Organic molecular structures ESCK4

### Special properties of carbon ESCK5

Carbon has a number of unique properties which influence how it behaves and how it bonds with other atoms:

- Carbon (Figure 4.2) has *four valence electrons* which means that each carbon atom can form a maximum of four bonds with other atoms. Because of the number of bonds that carbon can form with other atoms, organic compounds can be very complex.
  - Carbon can form bonds with other carbon atoms to form single, double or triple covalent bonds.
  - Carbon can also form bonds with other atoms like hydrogen, oxygen, nitrogen and the halogens.
  - Carbon can bond to form straight chain, branched, and cyclic molecules.

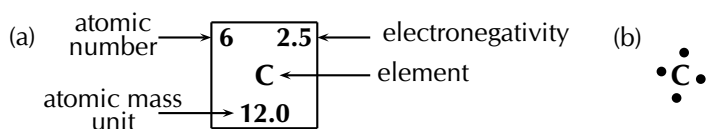



Figure 4.2: Carbon **(a)** as seen on the periodic table and **(b)** a Lewis dot representation.

**TIP**
Do not confuse organic compounds with *naturally produced* food. Organic compounds are often produced in a laboratory.

- Because of this, long *chain structures* can form. This is known as **catenation** - the bonding of atoms of the same element into longer chains. These chains can either be *unbranched* (Figure 4.3) or *branched* (have a branched group, Figure 4.4) and can contain single carbon-carbon bonds only, or double and triple carbon-carbon bonds as well.

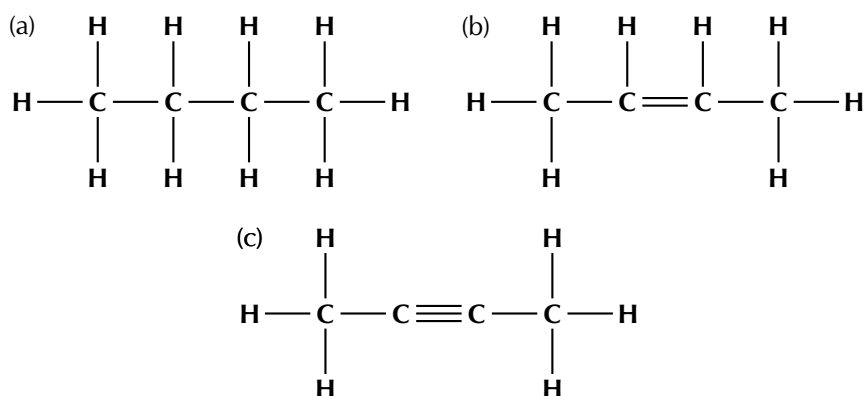



Figure 4.3: Unbranched carbon chains with **(a)** single carbon-carbon bonds, **(b)** single and double carbon-carbon bonds and **(c)** single and triple carbon-carbon bonds.

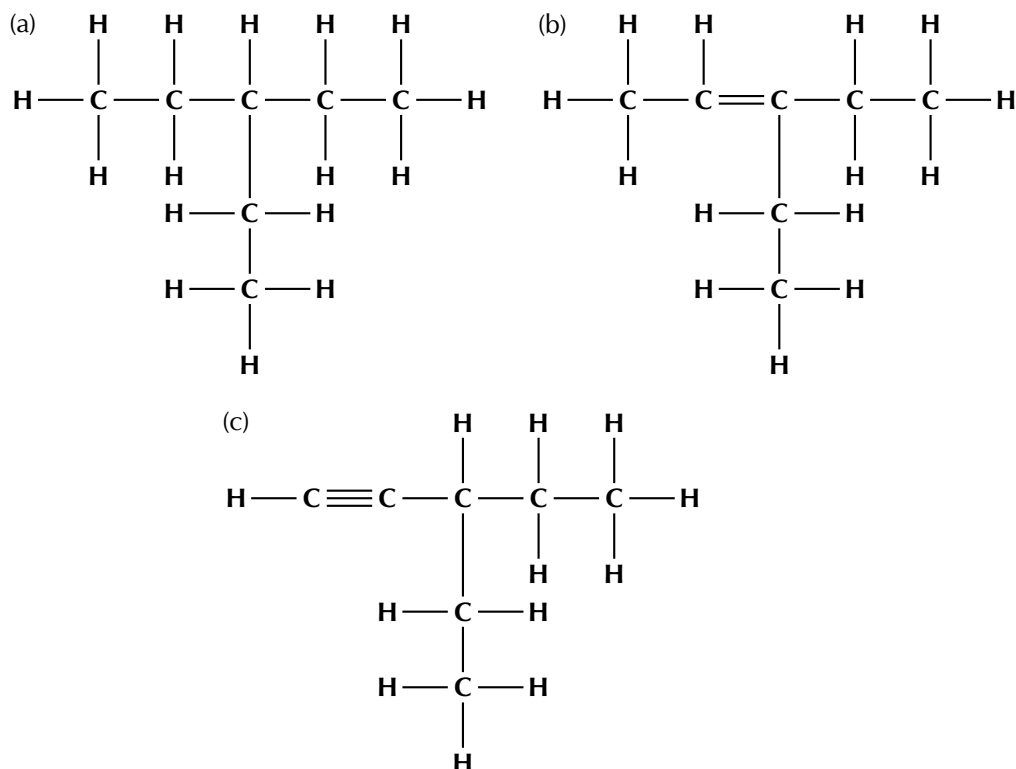
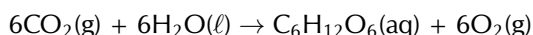



Figure 4.4: Branched carbon chains with **(a)** single carbon-carbon bonds, **(b)** single and double carbon-carbon bonds and **(c)** single and triple carbon-carbon bonds.

- Because of its position on the periodic table, most of the bonds that carbon forms with other atoms are *covalent*. Think for example of a C – C bond. The difference in electronegativity between the two atoms is zero, so this is a pure covalent bond. In the case of a C – H bond, the difference in electronegativity between carbon (2,5) and hydrogen (2,2) is so small that C – H bonds are almost purely covalent. The result of this is that most organic compounds are non-polar. This affects some of the properties of organic compounds.

### Sources of carbon

The main source of the carbon in organic compounds is **carbon dioxide** in the atmosphere. Plants use sunlight to convert carbon dioxide and water (inorganic compounds) into sugar (an organic compound) through the process of **photosynthesis**.

$$6CO_2(g) + 6H_2O(\ell) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$$

Plants are therefore able to make their own organic compounds through photosynthesis, while animals feed on plants or plant products in order to gain the organic compounds that they need to survive.

Other important sources of carbon are **fossil fuels** such as coal, petroleum and natural gas. This is because fossil fuels are themselves formed from the decaying remains of dead organisms (refer to Grade 11 for more information on fossil fuels).

## Representing organic molecules ESCK6

There are a number of ways to represent organic compounds. It is useful to know all of these so that you can recognise a molecule regardless of how it is shown. There are four main ways of representing a compound in two dimensions (on your page). We will use the examples of two molecules called 2-methylpropane and butane to help explain the difference between each.

- **Structural formula**

  The structural formula of an organic compound shows every bond between every atom in the molecule. Each bond is represented by a line. The structural formulae of 2-methylpropane and butane are shown in Figure 4.5.

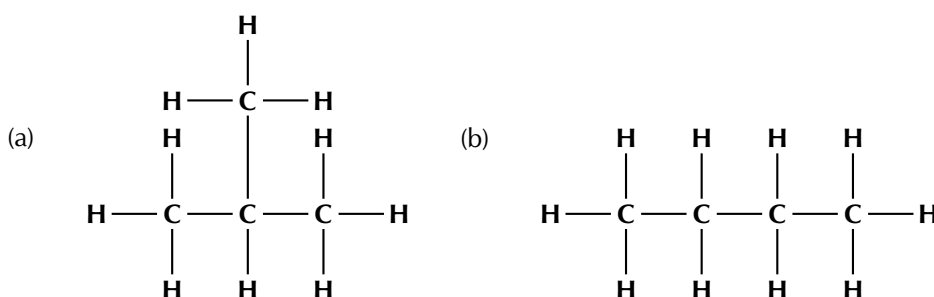



Figure 4.5: The structural formula of **(a)** 2-methylpropane and **(b)** butane.

H–C–H represents A carbon atom bonded to four hydrogen atoms

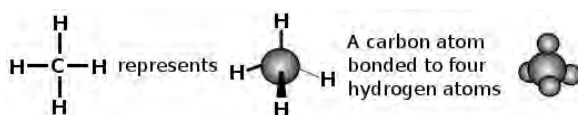



Figure 4.6: Different ways of representing a carbon atom bonding to four hydrogen atoms.

- **Semi-structural formula**

  It is possible to understand the structure of an organic molecule without writing out all the carbon-hydrogen bonds. This way of writing a structure is called a semi-structural formula and is shown in Figure 4.7.

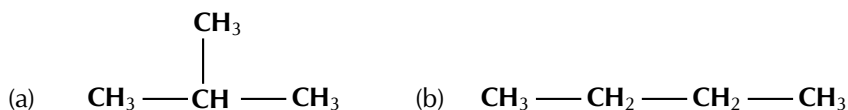



Figure 4.7: The semi-structural formulae of **(a)** 2-methylpropane and **(b)** butane.

  Compare these semi-structural representations with the structural representations shown in Figure 4.5.

- **Condensed structural formula**

  It is also possible to represent a molecule without showing any bonds between atoms at all. This is called a **condensed structural formula** (Figure 4.8). As for a semi-structural representation, the carbon atoms are grouped with the hydrogen atoms bonded directly to it. The bonds between these groups are not shown. Branched or substituent groups are shown in brackets after the carbon atom to which they are bonded.

(a) $\mathbf{CH_3CH(CH_3)CH_3}$ (b) $\mathbf{CH_3CH_2CH_2CH_3}$

Figure 4.8: The condensed structural formulae of **(a)** 2-methylpropane and **(b)** butane.

  Note that in Figure 4.8 (b) the two $CH_2$ groups can be abbreviated to $(CH_2)_2$. Compare these condensed structural representations with the structural (Figure 4.5) and the semi-structural representations (Figure 4.7).

- **Molecular formula**

  The molecular formula of a compound shows how many atoms of each type are in a molecule. The number of each atom is written as a subscript after the atomic symbol. The molecular formula of 2-methylpropane is:

  $\mathbf{C_4H_{10}}$

  This means that each molecule of 2-methylpropane consists of four carbon atoms and ten hydrogen atoms. The molecular formula of butane is also $C_4H_{10}$. Molecular formula gives no structural information about the compound.

**TIP**

A substituent is an atom or group of atoms that replaces a hydrogen atom on the main chain of an organic molecule. Therefore a brached group is a substituent. A halogen atom can also be a substituent.

Of course molecules are not two-dimensional so shown below are a few examples of different ways to represent methane ($CH_4$, Figure 4.9) and ethane ($C_2H_6$, Figure 4.10).

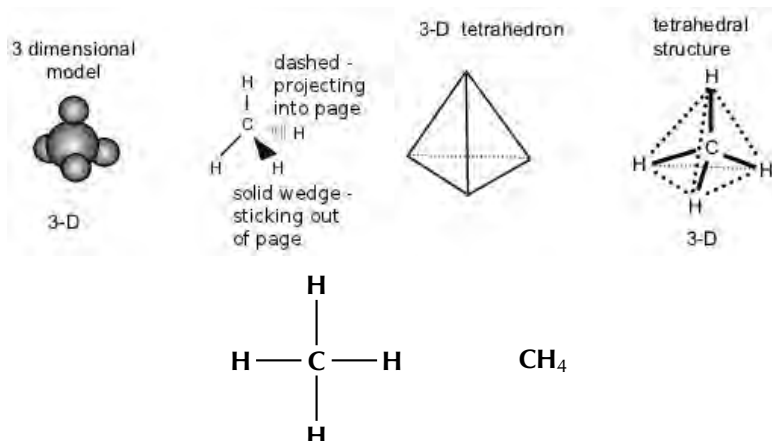



Figure 4.9: Different ways of representing methane.

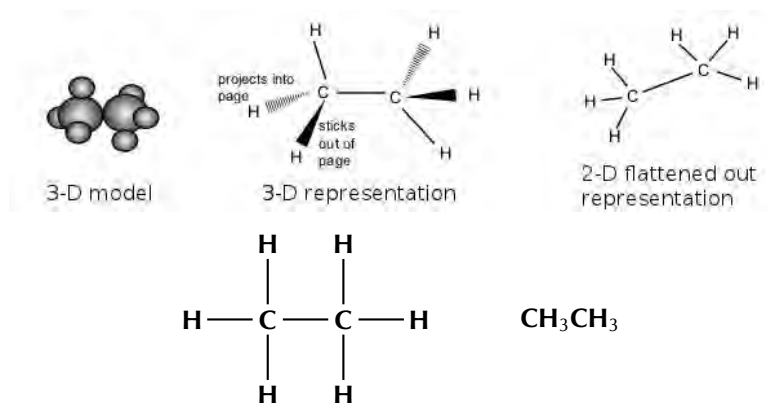



Figure 4.10: Different ways of representing ethane.

This means that butane can be represented in two dimensions as shown in Figure 4.11 (a) but it actually looks more like the three-dimensional representation given in Figure 4.11 (b).

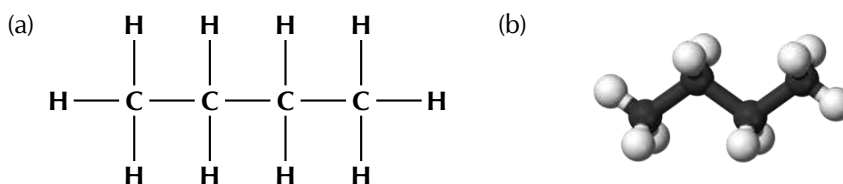
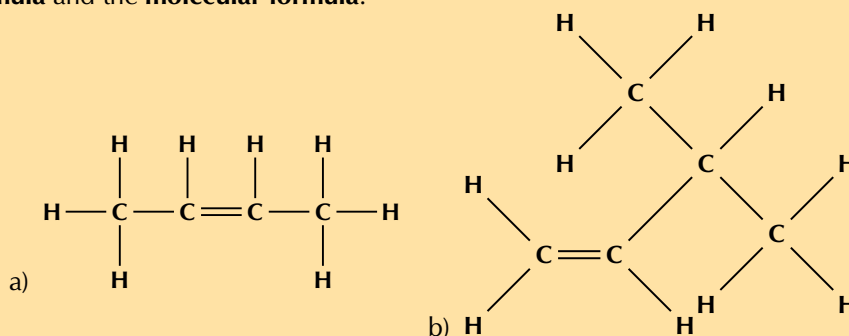



Figure 4.11: **(a)** Two-dimensional and **(b)** three-dimensional representations of butane.

**Exercise 4 – 1: Representing organic compounds**

1. For each of the following, give the **structural formula** and the **molecular formula**.

   a) $CH_3CH_2CH_3$  b) $CH_3CH_2CH(CH_3)CH_3$  c) $CH_3CH_3$

2. For each of the following organic compounds, give the **condensed structural formula** and the **molecular formula**.

3. Give two possible structural formulae for the compound with a molecular formula of $C_4H_{10}$.
4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27KT  2. 27KV  3. 27KW

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## Functional groups

ESCK7

The way in which a compound will react is determined by a particular characteristic of a group of atoms and the way they are bonded (e.g. double C–C bond, C–OH group). This is called the **functional group**. This group is important in determining how a compound will react. The same functional group will undergo the same or similar chemical reaction(s) regardless of the size of the molecule it is a part of. Molecules can have more than one functional group.

**DEFINITION:** *Functional group*

In organic chemistry a functional group is a specific group of atoms (and the bonds between them) that are responsible for the characteristic chemical reactions of those molecules.

In one group of organic compounds, called the **hydrocarbons**, the single, double and triple bonds between carbon atoms give rise to the alkanes, alkenes and alkynes, respectively. The double carbon-carbon bonds (in the alkenes) and triple carbon-carbon bonds (in the alkynes) are examples of functional groups.

In another group of organic compounds, called the **alcohols**, an oxygen and a hydrogen atom are bonded to each other to form the functional group (in other words an alcohol has an OH in it). All alcohols will contain an oxygen and a hydrogen atom bonded together in some part of the molecule. Table 4.1 summarises some of the common functional groups. We will look at these in more detail later in this chapter.

| Name of group | Functional group | Example | Structural Formula |
|---|---|---|---|
| **Alk*ane*** | —C—C— (with single bonds above and below each C) | Eth*ane* | H—C—C—H (each C also bonded to H above and below) |
| **Alk*ene*** | C=C (each C with two bonds) | Eth*ene* | H₂C=CH₂ (H above and below each C) |
| **Alk*yne*** | —C≡C— | Eth*yne* | H—C≡C—H |
| **Haloalkane/alkyl halide** | —C—X (X = F,Cl,Br,I) | Chloromethane | H—C—Cl (H above and below C) |
| **Alcoh*ol* / alkan*ol*** | —C—O—H | Methan*ol* | H—C—H with O—H above and H below C |
| **Carboxylic acid** | —C(=O)—O—H | Methan*oic acid* | H—C(=O)—O—H |

Table 4.1: Some functional groups of organic compounds.

There are some important points to note as we discuss functional groups:

- The beginning of a compound name (prefix) comes from the number of carbons in the longest chain:

| meth- | 1 carbon atom |
|---|---|
| eth- | 2 carbon atoms |
| prop- | 3 carbon atoms |
| but- | 4 carbon atoms |

- The end of a compound name (suffix) comes from the functional group, e.g. an alkane has the suffix -ane. Refer to the examples in Table 4.1.

For more information on naming organic molecules see Section 4.3.

## Saturated and unsaturated structures ESCK8

Hydrocarbons that contain only single bonds are called **saturated** hydrocarbons because each carbon atom is bonded to as many hydrogen atoms as possible. Figure 4.12 shows a molecule of ethane, which is a saturated hydrocarbon.
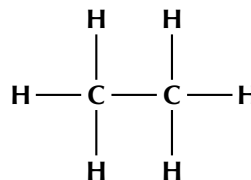
Figure 4.12: A saturated hydrocarbon, ethane.

**DEFINITION:** *Saturated compounds*

A **saturated** compound has no double or triple bonds (i.e. they have single bonds only). All carbon atoms are bonded to four other atoms.

Hydrocarbons that contain double or triple bonds are called **unsaturated** hydrocarbons because they don't contain as many hydrogen atoms as possible.

**DEFINITION:** *Unsaturated compounds*

An **unsaturated** compound contains double or triple bonds. A carbon atom may therefore be bonded to only two or three other atoms.

Figure 4.13 shows molecules of ethene and ethyne which are unsaturated hydrocarbons. If you compare the number of carbon and hydrogen atoms in a molecule of ethane and a molecule of ethene, you will see that the number of hydrogen atoms in ethene is *less* than the number of hydrogen atoms in ethane despite the fact that they both contain two carbon atoms. In order for an unsaturated hydrocarbon compound to become saturated, one of the two (or three) bonds in a double (or triple) bond has to be broken, and additional atoms added.
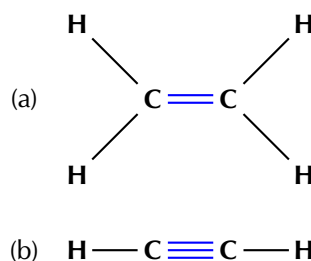
Figure 4.13: Unsaturated hydrocarbons: **(a)** ethene and **(b)** ethyne.

See video: 27KX at www.everythingscience.co.za

## The hydrocarbons ESCK9

**FACT**
An aliphatic compound is one that does not contain an aromatic ring:

benzene

The simplest aromatic compound is benzene. There are aliphatic cyclic compounds, but if a compound contains an aromatic ring it is an aromatic compound, not an aliphatic one.

Let us first look at a group of organic compounds known as the **hydrocarbons**.

**DEFINITION:** *Hydrocarbon*

An organic molecule which contains only carbon and hydrogen atoms with no other functional groups besides single, double or triple carbon-carbon bonds.

The hydrocarbons that we are going to look at are called **aliphatic compounds**. The aliphatic compounds are divided into *acyclic compounds* (chain structures) and *cyclic compounds* (ring structures). The chain structures are further divided into structures that contain only *single bonds* (**alkanes**), those that contain at least one *double bond* (**alkenes**) and those that contain at least one *triple bond* (**alkynes**).

Cyclic compounds (which will not be covered in this book) include structures such as a *cyclopentane ring*, which is found in insulating foam and in appliances such as fridges and freezers. Figure 4.14 summarises the classification of the hydrocarbons.
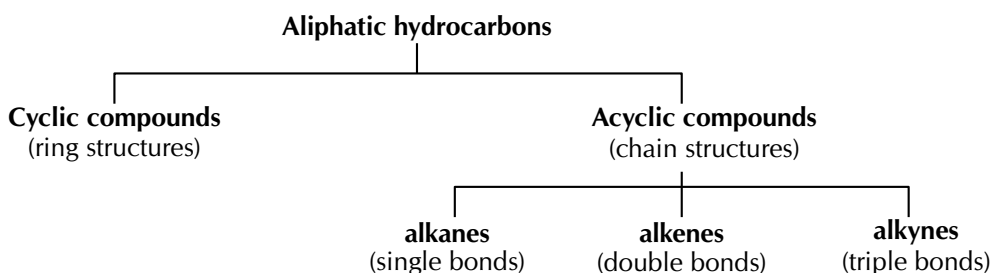
Figure 4.14: The classification of the aliphatic hydrocarbons.

We will now look at each of the acyclic, aliphatic hydrocarbon groups in more detail.

### The alkanes

The alkanes are hydrocarbons that only contain *single covalent bonds* between their carbon atoms. This means that they are *saturated* compounds and are quite unreactive. The simplest alkane has only one carbon atom and is called **methane**. This molecule is shown in Figure 4.15.

Figure 4.15: The **(a)** structural and **(b)** molecular formula representations of methane.

The second alkane in the series has two carbon atoms and is called **ethane**. This is shown in Figure 4.16.
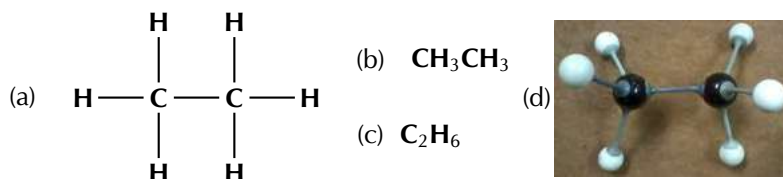
Figure 4.16: The **(a)** structural, **(b)** condensed structural and **(c)** molecular formula representations of ethane. **(d)** An atomic model of ethane.

**FACT**
Some fungi use alkanes as a source of carbon and energy. One fungus *amorphotheca resinae* (also known as kerosene fungus) prefers the alkanes used in aviation fuel, and this can cause problems for aircraft in tropical areas.

The third alkane in the series has three carbon atoms and is called **propane** (Figure 4.2).
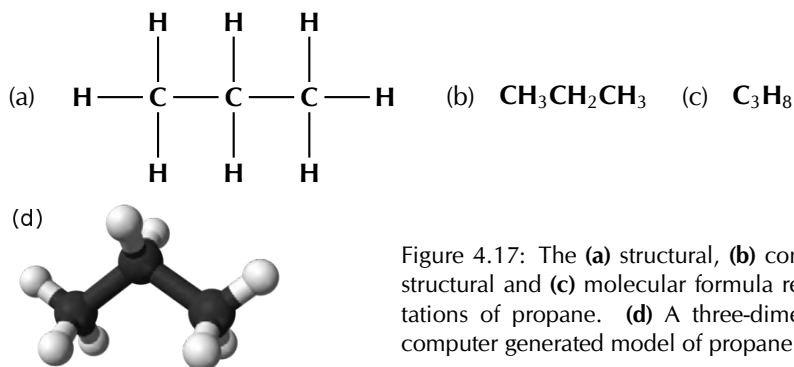
Figure 4.17: The **(a)** structural, **(b)** condensed structural and **(c)** molecular formula representations of propane. **(d)** A three-dimensional computer generated model of propane.

When you look at the molecular formula for each of the alkanes, you should notice a pattern developing. For each carbon atom that is added to the molecule, two hydrogen atoms are added. In other words, each molecule differs from the one before it by $CH_2$. This is called a *homologous series*.

**DEFINITION:** *Homologous series*

A homologous series is a series of compounds with the same general formula. All molecules in this series will contain the same functional groups.

The general formula is similar to both the molecular formula and the condensed structural formula. The functional group is written as it would be in the condensed structural formula (to make it more obvious), while the rest of the atoms in the compound are written in the same style as the molecular formula. The alkanes have the **general formula**: $C_nH_{2n+2}$.

- The alkanes are the most important source of fuel in the world and are used extensively in the chemical industry.
- Alkanes that contain four or less carbon atoms are gases (e.g. methane and ethane).
- Others are liquid fuels (e.g. octane, an important component of petrol).
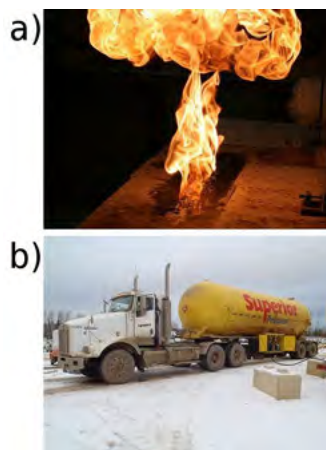
Figure 4.18: **(a)** Methane gas bubbles burning and **(b)** propane (under high pressure) being transported by truck.

Figure 4.19: Liquid fuels that contain octane are kept in tanks at petrol stations.

### The alkenes

In the alkenes there must be at least one double bond between two carbon atoms. This means that they are *unsaturated* and are *more reactive* than the alkanes. The simplest alkene is ethene (also known as ethylene), which is shown in Figure 4.20.

**TIP**

Note that if an alkene has two double bonds, it is called a **diene**.

If you don't understand the names of compounds, don't worry. We will go into more detail on this later in the chapter.
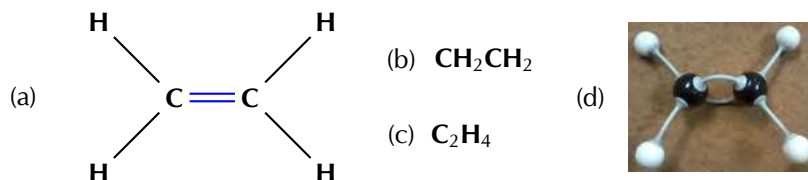
Figure 4.20: The **(a)** structural, **(b)** condensed structural and **(c)** molecular formula representations of ethene. **(d)** An atomic model of ethene.

As with the alkanes, the alkenes also form a homologous series. They have the **general formula**: $\mathbf{C_nH_{2n}}$. The second alkene in the series would therefore be $C_3H_6$. This molecule is known as propene (Figure 4.21).
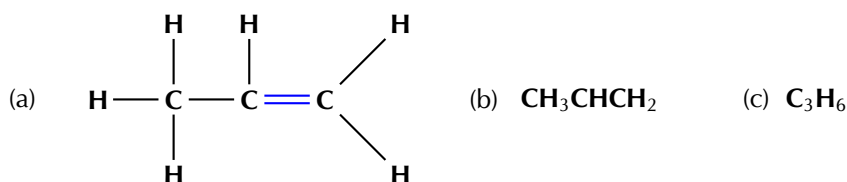
Figure 4.21: The **(a)** structural, **(b)** condensed structural and **(c)** molecular formula representations of propene.

There can be more than one double bond in an alkene as shown in Figure 4.22. The naming of these compounds is covered in Section 4.3, IUPAC naming and formulae.
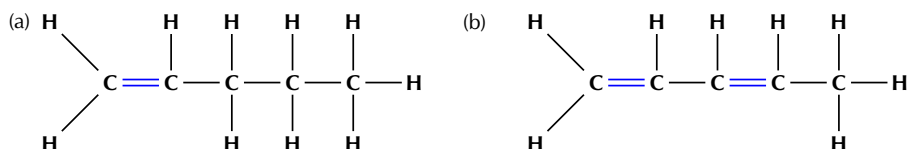
Figure 4.22: The structural representations of **(a)** pent-1-ene and **(b)** pent-1,3-diene.

The alkenes are more reactive than the alkanes because they are unsaturated. As with the alkanes, compounds that have four or less carbon atoms are gases at room temperature. Those with five or more carbon atoms are liquids.

The alkenes have a variety of uses:

- For example, ethene is a chemical compound used in plants to stimulate the ripening of fruits and the opening of flowers.
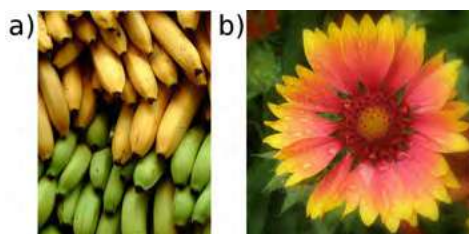
Figure 4.23: **(a)** Unripe (green) and ripe (yellow) bananas and **(b)** a flowering plant.

- Propene is an important compound in the petrochemicals industry. It is used to make polypropylene (see Section 4.7 for more information) and is also used as a fuel gas for other industrial processes.

**FACT**
Acetylene is the industrial name for the organic compound ethyne. The raw materials that are needed to make acetylene are calcium carbonate and coal. An important use of acetylene is in oxyacetylene gas welding. The fuel gas burns with oxygen in a torch. Because the combustion of alkenes and alkynes is exothermic an incredibly high heat is produced, which is hot enough to melt metal.

**FACT**
Liquid bromine is highly corrosive and toxic. Handle with extreme care!

Figure 4.24: A lamp made of polypropylene. Propene is used to make polypropylene.

**The alkynes**

In the alkynes there must be at least one triple bond between two of the carbon atoms. They are unsaturated compounds and are therefore more reactive than alkanes. Their **general formula** is $C_nH_{2n-2}$. For example **but-1-yne** has the molecular formula $C_4H_6$. The simplest alkyne is ethyne (Figure 4.25), also known as acetylene. Many of the alkynes are used to synthesise other chemical products.

(a) $H-C\equiv C-H$ (b) **CHCH** (c) $C_2H_2$

(d)
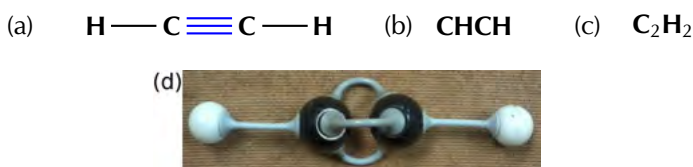
Figure 4.25: The **(a)** structural, **(b)** condensed structural and **(c)** molecular representations of ethyne (acetylene). **(d)** An atomic model of ethyne.

Remember that organic molecules do not need to be straight chains. They can have branched groups as well, as shown in Figure 4.26.

Figure 4.26: A methyl branched group on carbon 2 of butane (2-methylbutane).

A summary of the relative reactivity and the homologous series that occur in the hydrocarbons is given in Table 4.2.

| Functional group | Homologous series | Reactivity |
|---|---|---|
| alk***ane*** | $C_nH_{2n+2}$ | low reactivity |
| alk***ene*** | $C_nH_{2n}$ | high reactivity |
| alk***yne*** | $C_nH_{2n-2}$ | high reactivity |

Table 4.2: A summary of the homologous series of the hydrocarbons.

**Experiment: Saturated vs. unsaturated compounds**

**Aim:**
To study the effect of bromine water and potassium permanganate on saturated and unsaturated compounds.

**Apparatus:**
**WARNING!**

---

**Liquid bromine (required to make bromine water) is a highly volatile, corrosive and toxic compound. Please handle with care: wear the appropriate safety clothing including gloves, labcoat, safety glasses and mask. Work in a fumehood. If you do not have the apparatus to handle liquid bromine safely, use potassium permanganate only.**

---

- cyclohexane, cyclohexene, bromine water ($Br_2(aq)$), potassium permanganate ($KMnO_4$) in an acidic solution
- 4 glass containers (test tubes/beakers/shallow basins), two A4 sheets of paper
- 2 plastic pipettes

**Method:**

1. Label one piece of paper *A* and the other piece of paper *B*.
2. Place 20 ml of cyclohexane into a container and place the container on paper A.
3. Place 20 ml of cyclohexane into a container and place the container on paper B.
4. Repeat steps 2 and 3 with cyclohexene.
5. Take 12 ml of bromine water and add it to the beaker of cyclohexane on paper A. Observe any colour changes.
6. Repeat step 5 with the beaker of cyclohexene on paper A.
7. Take 12 ml of $KMnO_4$ and add it to the beaker of cyclohexane on paper B. Observe any colour changes.
8. Repeat step 7 with the beaker of cyclohexene on paper B.

**Results:**

Record your results in the table.

Cyclohexane is an *alkane*, cyclohexene is an *alkene*.

| Compound | Initial colour | Solution added | Final colour |
|---|---|---|---|
| cyclohexane | | bromine water | |
| cyclohexane | | $KMnO_4$ | |
| cyclohexene | | bromine water | |
| cyclohexene | | $KMnO_4$ | |

**Questions:**

- Which of these compounds (cyclohexane, cyclohexene) is saturated and which is unsaturated?
- What colour changes did you observe with the alkane compound?
- What colour changes did you observe with the alkene compound?
- Can you suggest a reason for the differences?

**Discussion and conclusion:**

Bromine water and $KMnO_4$ both have intense colours. Cyclohexane is a saturated, colourless liquid. When bromine water and $KMnO_4$ are added to the cyclohexane there is no reaction and the solution becomes the colour of the bromine water or $KMnO_4$.

Cyclohexene is also a colourless liquid, but it is unsaturated. This results in a reaction with bromine water and with $KMnO_4$. Cyclohexene will form a bromoalkane with bromine water. Bromoalkanes are colourless liquids and the solution will be colourless - liquid bromine is decolourised by cyclohexene. Similarly $KMnO_4$ will be decolourised by the cyclohexene.

**Exercise 4 – 2: The hydrocarbons**

1. Answer these questions on the hydrocarbons.
   a) What is the difference between the alkanes, alkenes and alkynes?
   b) Give the general formula for the alkynes

c) Of the alkanes, alkenes and alkynes which is:

i. saturated

ii. unsaturated

d) Which series is the least reactive? Explain why.

2. Draw the structural formulae for:

a) $CHCCH_3$

b) $CH_3CH_2CH_3$

c) $CH_2CHCH_3$

3. Fill in the table:

| Compound | Saturated or unsaturated? |
|---|---|
| $CH_3CH_2CH_3$ | |
| $H-C\equiv C-H$ | |
| $CH_3CH_2CHCHCH_2CH_2CH_2CH_3$ | |
| heptane | |
| $CH_2=CH-CH_2-CH_3$ | |

4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27KY 2. 27KZ 3. 27M2

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## The alcohols ESCKB

An alcohol is any organic compound where there is a *hydroxyl* functional group (–OH) bound to a carbon atom. The **general formula** for a simple alcohol is $C_nH_{2n+1}OH$.

The simplest and most commonly used alcohols are methanol and ethanol (Figures 4.27 and 4.28).

Figure 4.27: The **(a)** structural, **(b)** condensed structural and **(c)** molecular formula representations of methanol.

Figure 4.28: The **(a)** structural, **(b)** condensed structural and **(c)** molecular formula representations of ethanol. **(d)** An atomic model of ethanol.

There are three possible types of carbon atoms - primary, secondary and tertiary. A *primary* carbon is attached to only one other carbon atom. A *secondary* carbon is attached to two other carbon atoms, while a *tertiary* carbon atom is attached to three other carbon atoms.

There can be a functional group attached to these different types of carbon atom. When a hydroxyl (–OH) functional group is attached to a primary carbon atom it is called a **primary alcohol**. For a **secondary alcohol** the hydroxyl is bonded to a secondary

carbon atom. When the hydroxyl is bonded to a tertiary carbon atom it is a **tertiary alcohol**. Examples are given below.

(a) **Primary Alcohols** (C atom at the end of a chain)
-OH (hydroxyl group) is bonded to a carbon atom that is bonded to only one other carbon atom
**butan-1-ol**

(b) **Secondary Alcohols** (C atom inside a chain)
-OH group is bonded to a carbon atom that is bonded to two other carbon atoms
**butan-2-ol**

(c) **Tertiary Alcohols** (needs a branched chain)
-OH group is bonded to a carbon atom that is bonded to three other carbon atoms
**2-methylpropan-2-ol**

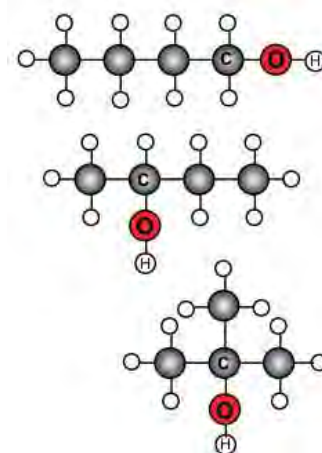



Figure 4.29: A **(a)** primary (butan-1-ol), **(b)** secondary (butan-2-ol) and **(c)** tertiary (2-methylpropan-2-ol) alcohol.

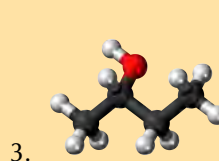
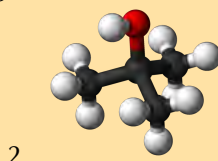
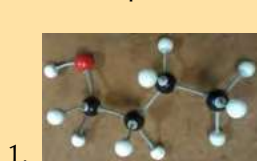
**FACT**

**Methanol is toxic**. If ingested it forms formic acid or formate salts, which damage the central nervous system and can cause *blindness, coma* or *death*.

The alcohols have a number of different uses:

- methylated spirits is ethanol with methanol added
- all alcohols are toxic, but in low concentrations ethanol can be used in alcoholic drinks
- ethanol is the only alcohol used in alcoholic drinks
- ethanol is used as an industrial solvent
- methanol and ethanol can both be used as a fuel and they burn more cleanly than petrol or diesel.
- ethanol is used as a solvent in medical drugs, perfumes and plant essences
- ethanol is an antiseptic

### Exercise 4 – 3: The alcohols

Give the structural and condensed structural formula for the following alcohols. State, with reasons, whether the compound is a primary, secondary, or tertiary alcohol.
(Note: a black ball represents a carbon atom, a white ball represents a hydrogen atom, and a red ball represents an oxygen atom)

1. 
2. 
3. 
4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27M3 2. 27M4 3. 27M5

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**FACT**
CFC stands for *chlorofluorocarbons*. Due to their low toxicity and low reactivity, CFCs were widely used in refrigeration and as propellants in aerosols. However, the low reactivity means that CFCs can get into the upper atmosphere where they are degraded by UV light and damage the ozone layer.

**FACT**
Chloroform ($CHCl_3$) was used as an anesthetic for years. However, aside from causing dizziness, fatigue and headaches, it was discovered to be toxic, often fatally so. Even non-fatal doses can cause damage to the kidneys and liver. Chloroform can sometimes be found in cough syrups, although not often anymore.

## Alkyl halides ESCKC

Alkyl halides are hydrocarbons with one hydrogen atom replaced by a halogen atom (F, Cl, Br, I). The **alkyl** is due to the fact that a hydrocarbon branched group has the suffix *-yl* and is one of the three hydrocarbons: alk*anes*, alk*enes* or alk*ynes*. These *alk*yl groups contain one or more halogen atoms, which leads to the name alkyl halides. Our focus will be on the alk*ane* alkyl halides also known as the haloalkanes (or halogenoalkanes) (see Table 4.1).
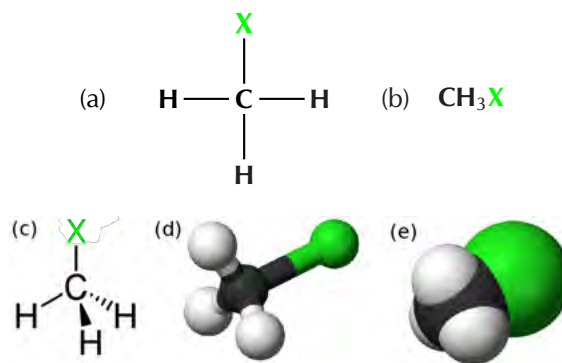
Figure 4.30: Representations of a halomethane where X can be F, Cl, Br or I: **(a)** structural, **(b)** molecular formula, **(c)** 3-D line drawing, **(d)** 3-D ball and stick model and **e)** 3-D space-filling model.
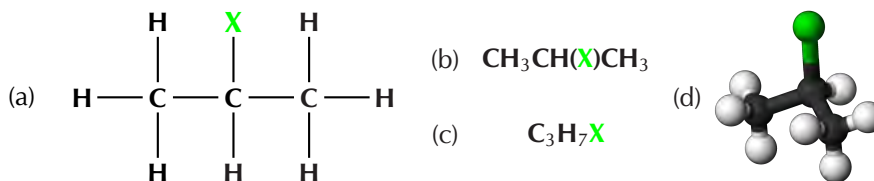
Figure 4.31: Representations of 2-*halo*propane where X can be F, Cl, Br or I: **(a)** structural, **(b)** condensed structural, **(c)** molecular formula and **(d)** a ball and stick model.

Note that the halogen atom is called a *substituent*.
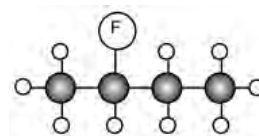
Figure 4.32: A fluorine atom as a substituent on carbon 2 of butane (2-fluorobutane).

Remember the branched chain shown in Figure 4.26. That branched chain is also called a substituent.

**DEFINITION:** *Substituent*

A substituent is *an atom or group of atoms* bonded to a carbon chain. This can be an inorganic atom (e.g. halogen) or an alkyl group that is shorter than the main group.

An organic compound is always named in accordance with the longest chain of carbon atoms that contains the functional group. If the substituent is an alkyl group it is known as a branched chain.

Some uses of haloalkanes include:

- in fire extinguishers
- as aerosol propellants
- in refrigeration
- generating foamed plastics
- solvents in dry cleaning processes (not actually *dry*, but no water is required)

**Extension**

Chloroform

Haloalkanes can contain more than one halogen atom. Chloromethanes are substances that can be used as anaesthetics during operations. One example is trichloromethane, also known as *chloroform* (Figure 4.33).
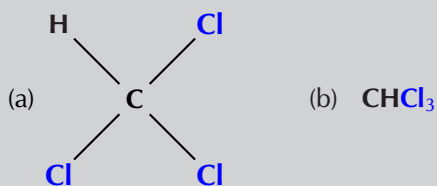
Figure 4.33: The **(a)** structural and **(b)** molecular formula representations of trichloromethane (chloroform).

**Exercise 4 – 4: Haloalkanes**

1. Answer these questions on the haloalkanes.
   a) Give the general formula for the haloalkanes with only one halogen atom
   b) Are haloalkanes saturated compounds?
2. Draw the structural formulae for:
   a) $CH_2(Br)CH_2CH_3$
   b) $CH_3CH(Cl)CH_2CH_3$
   c) $CH_2(F)CH_3$
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27M6    2. 27M7

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## Carbonyl-containing compounds ESCKD

The carbonyl group consists of a carbon atom that is joined to an oxygen by a double bond (see Figure 4.34).

In Figure 4.34 **R′** and **R** are used to represent the rest of the atoms in the molecule. For example **R** could represent an alkyl chain, or a hydrogen atom.

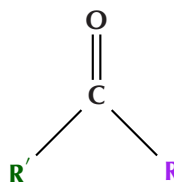



Figure 4.34: A compound containing a carbonyl group.

### Aldehydes and ketones

If the functional group is on the *end* of the carbon chain, the organic compound is called an **aldehyde** (Figure 4.35 (a)). Being at the *end* of the chain means that **R′** or **R** represents a hydrogen atom. The simplest aldehyde is *methanal*.

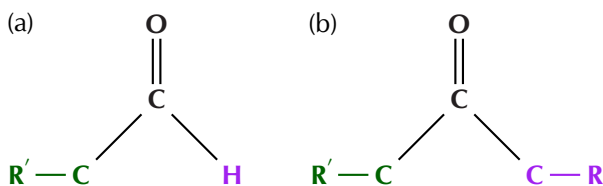



Figure 4.35: **(a)** An aldehyde and **(b)** a ketone.

**TIP**

Note that the condensed structural formula for an aldehyde ends in **CHO** not COH. This is because COH could be confused with the hydroxyl (−OH) group of an alochol.

**FACT**

The molecular formulae representations for butanal and butanone are identical ($C_4H_8O$). This is why structural and condensed structural representations are necessary.

The aldehyde containing 4 carbon atoms, butanal, is illustrated in Figure 4.2. In this example **R** represents H and **R′** represents $CH_3CH_2CH_2$.

```
         H     H     H     O
         |     |     |     ||
(a)  H — C  —  C  —  C  —  C — H      (b) CH3CH2CH2CHO      (c) C4H8O
         |     |     |
         H     H     H
```

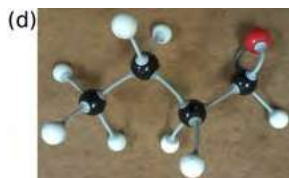
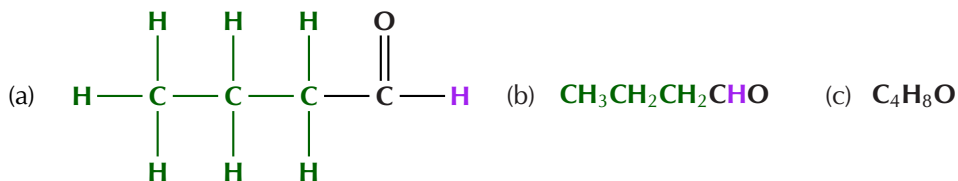



Figure 4.36: The **(a)** structural, **(b)** condensed structural and **(c)** molecular formula representations of butanal. **(d)** An atomic model of butanal.

Some uses of aldehydes include:

- in resins (over 6 million tons of formaldehyde are produced per year)
- in the production of plasticisers and alcohols used in detergents
- in perfumes and flavourants

If the carbonyl group is in the middle of the carbon chain, the compound is called a **ketone** (Figure 4.35 (b)). Being in the *middle* of the chain means that **R′** and **R** *cannot* represent H. The simplest ketone is *propanone* (also known as acetone, the compound in nail varnish remover), which contains three carbon atoms. The ketone containing 4 carbon atoms, butanone, is illustrated in Figure 4.2.

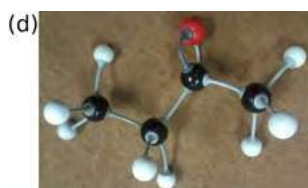
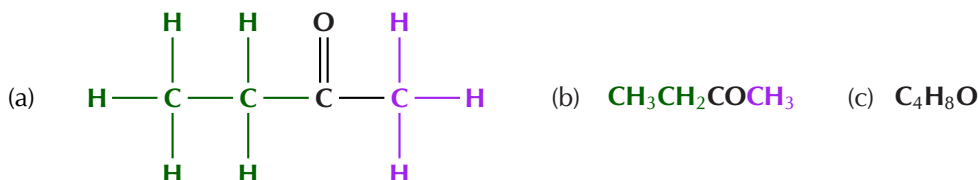



Figure 4.37: The **(a)** structural, **(b)** condensed structural and **(c)** molecular formula representations of butanone. **(d)** An atomic model of butanone.

Some uses of ketones include:

- as solvents
- in the production of polymers
- in the production of pharmaceuticals

The **general formula** for both the aldehydes and ketones can be written as: $\mathbf{C_nH_{2n}O}$. This means that they cannot be told apart from their general formula alone. There are more complex general formulas that allow aldehydes and ketones to be distinguished, but they are not covered in this book.

### Carboxylic acids

Carboxylic acids are organic acids that are characterised by having a carboxyl group, written as −COOH. In a carboxyl group a carbon atom is double-bonded to an oxygen atom (carbonyl group), and it is also bonded to a hydroxyl group (**R**). The simplest carboxylic acid, methanoic acid, is shown in Figure 4.38 and ethanoic acid is shown in Figure 4.2.

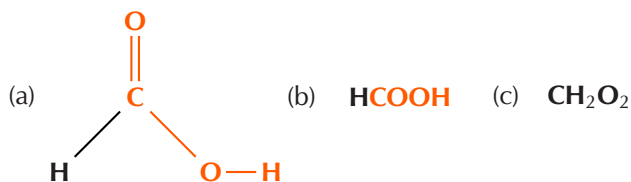



Figure 4.38: The **(a)** structural, **(b)** condensed structural and **(c)** molecular formula representations of methanoic acid.

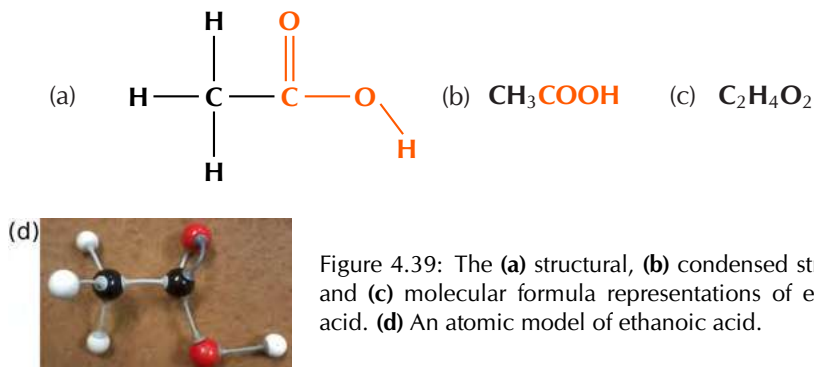



Figure 4.39: The **(a)** structural, **(b)** condensed structural and **(c)** molecular formula representations of ethanoic acid. **(d)** An atomic model of ethanoic acid.

**FACT**

A certain type of ant, called formicine ants, manufacture and secrete formic acid, which is used to defend themselves against other organisms that might try to eat them.

Carboxylic acids are widespread in nature. Methanoic acid (also known as *formic acid*) has the formula HCOOH and is found in insect stings. Ethanoic acid ($CH_3COOH$), or *acetic acid*, is the main component of vinegar. More complex organic acids also have a variety of different functions. Benzoic acid for example, is used as a food preservative. Carboxylic acids have the **general formula**: $C_nH_{2n+1}COOH$.

Ethanoic acid can be produced through the oxidation of ethanol upon exposure to the oxygen in air. This is why wine that is left too long can taste acidic. Wine can easily go sour if exposed to the oxygen molecules ($O_2$) in the air, especially if the weather is warm.

**ethanol + oxygen → ethanoic acid + water**

$$\mathrm{H{-}\overset{H}{\underset{H}{C}}{-}\overset{H}{\underset{H}{C}}{-}O{-}H} + O_2 \longrightarrow \mathrm{H{-}\overset{H}{\underset{H}{C}}{-}\overset{O}{\overset{\|}{C}}{-}O{-}H} + H_2O$$

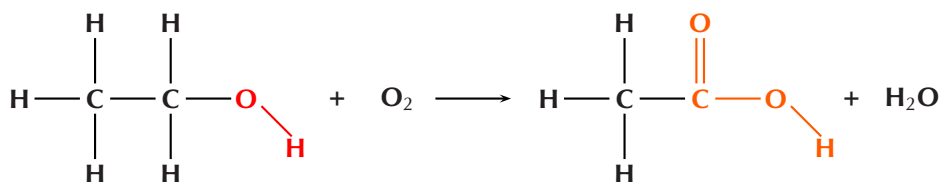
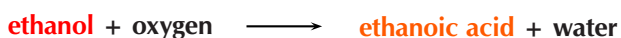
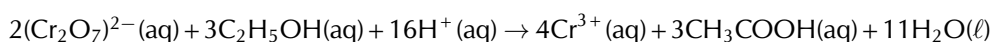



Figure 4.40: The oxidation of wine.

The oxidation of ethanol to ethanoic acid can also be seen in the reaction of ethanol with potassium dichromate:

$$2(Cr_2O_7)^{2-}(aq) + 3C_2H_5OH(aq) + 16H^+(aq) \rightarrow 4Cr^{3+}(aq) + 3CH_3COOH(aq) + 11H_2O(\ell)$$

The colour change that occurs is shown in the image below and the following video:

See video: 27M8 at www.everythingscience.co.za

Figure 4.41: The different colours of potassium dichromate (left) and potassium dichromate and ethanol (right). (Screenshot taken from video by beggar098 on YouTube)

**TIP**
Esters will be dealt with in much greater detail in Section 4.7.

**Case study: Breathalysers**

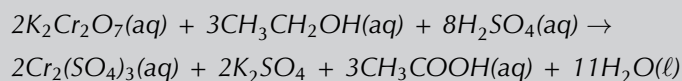
Read the following extract taken from HowStuffWorks (12/08/13):

*The* ***Breathalyzer*** *device contains:*

- *A system to sample the breath of the suspect*
- *Two glass vials containing the chemical reaction mixture*
- *A system of photocells connected to a meter to measure the color change associated with the chemical reaction*

*To measure alcohol, a suspect breathes into the device. The breath sample is bubbled in one vial through a mixture of sulfuric acid, potassium dichromate, silver nitrate and water. The principle of the measurement is based on the following chemical reaction:*

$2K_2Cr_2O_7(aq) + 3CH_3CH_2OH(aq) + 8H_2SO_4(aq) \rightarrow$

$2Cr_2(SO_4)_3(aq) + 2K_2SO_4 + 3CH_3COOH(aq) + 11H_2O(\ell)$

*In this reaction:*

1. *The* ***sulfuric acid removes the alcohol from the air*** *into a liquid solution.*
2. *The* ***alcohol reacts with potassium dichromate*** *to produce: chromium sulfate, potassium sulfate, acetic acid, water*

*The silver nitrate is a* ***catalyst****, a substance that makes a reaction go faster without participating in it. The sulfuric acid, in addition to removing the alcohol from the air, also might provide the acidic condition needed for this reaction.*

*During this reaction, the reddish-orange dichromate ion* ***changes color*** *to the green chromium ion when it reacts with the alcohol; the degree of the color change is directly related to the level of alcohol in the expelled air. To determine the amount of alcohol in that air, the reacted mixture is compared to a vial of unreacted mixture in the* ***photocell system****, which produces an* ***electric current*** *that causes the needle in the meter to move from its resting place. The operator then rotates a knob to bring the needle back to the resting place and reads the level of alcohol from the knob – the more the operator must turn the knob to return it to rest, the greater the level of alcohol.*

Break into groups of three or four. Research breathalysers and then report your information to the class.

Make sure to cover the following areas:

- The effect of alcohol on the body
- The effect of alcohol on reaction times
- The origins of the breathalyser
- The term *mouth alcohol* and its effect on breathalyser tests.

### Esters

When an alcohol reacts with a carboxylic acid, an **ester** is formed. Most esters have a characteristic smell. In the reaction a molecule of water is removed from the two compounds and a new bond is formed between what remains of the alcohol and the carboxylic acid. A **catalyst** is required in this reaction, in this case it must be an inorganic acid (e.g. $H_2SO_4$). An example is shown in Figure 4.42.

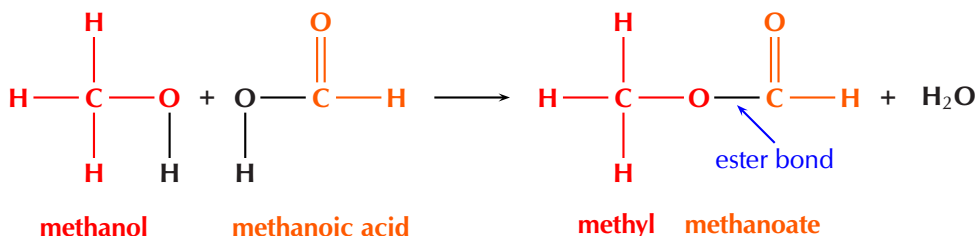



Figure 4.42: The formation of an ester and water from an alcohol and carboxylic acid.

**FACT**
The esterification process is reversible with large quantities of water (although it can be slow). In an acidic environment the reaction speeds up. Reversible reactions are covered in greater detail in Chapter 8.

The esterification process with methanol and methanoic acid is shown with atomic models in Figure 4.43. Esters have the **general formula**: $C_nH_{2n}O_2$. This general formula can also be applied to carboxylic acids, but the more complex general formula for esters alone is not covered in this book.

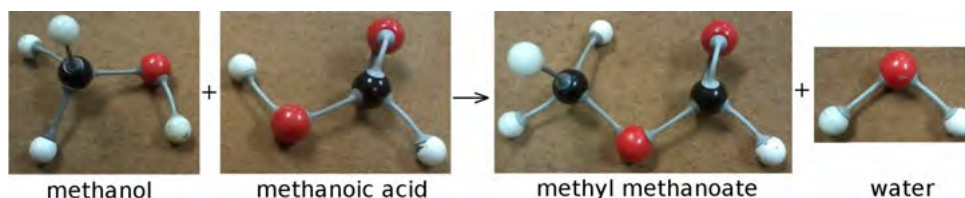



Figure 4.43: The esterification process of methanol and methanoic acid to methyl methanoate and water, shown with three-dimensional model kits.

Some common uses for esters are:

- in cosmetics and beauty products because they typically have a fruity smell, making them good as artificial flavourants and scents
- in nail varnish remover and model plane glue
- as solvents for non-water soluble compounds (e.g. oils, resins) because the ester of a specific carboxylic acid will be less water soluble than the carboxylic acid
- as plasticisers because esters can make a compound less brittle, and more flexible

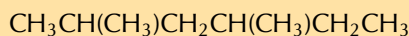
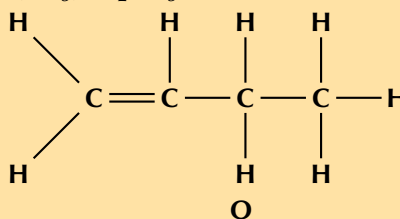
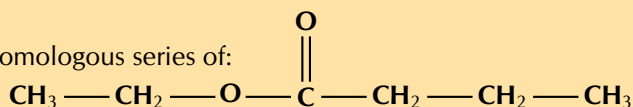
**Exercise 4 – 5: Carbonyl compounds**

1. Answer these questions on carbonyl compounds.
   a) What other functional group does a carboxylic acid have in addition to a carbonyl group?
   b) What is the main difference between aldehydes and ketones
   c) What two reactants are required to make an ester?
   d) How is ethanoic acid produced?
2. Draw the structural formulae for each of the following compounds. What series does each compound belong to?
   a) $CH_3COCH_3$ b) $CH_3CH_2COOH$ c) $CH_3CH_2CHO$ d) $CH_3COOCH_3$
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27M9 2. 27MB

## Exercise 4 – 6: Functional groups

1. Write down the:
   a) name of the homologous series of:
   $CH_3CH(CH_3)CH_2CH(CH_3)CH_2CH_3$

   b) general formula of:

   c) name of the homologous series of:
   $CH_3 - CH_2 - O - C(=O) - CH_2 - CH_2 - CH_3$

   d) structural formula of: $CH_3CH_2COOH$

2. Look at the list of organic compounds in the table below:

| Organic compound | Homologous series |
|---|---|
| $CH_3CH_2CH_2COOH$ | |
| H O H H H<br>H — C — C — O — C — C — C — H<br>H H H H | |
| $CH_3CHO$ | |
| H H H<br>H — C — C — C — H<br>H H H | |
| $CH_3CCCH_2CH_2CH_2CH_3$ | |

   a) Complete the table by identifying the functional group of each compound.
   b) Give the structural representation of the compounds represented by condensed structural formulae.

3. A chemical reaction takes place and ethyl methanoate is formed.
   a) Identify the homologous series to which ethyl methanoate belongs?
   b) Name the two types of reactants used to produce this compound in a chemical reaction.
   c) Give the structural formula of ethyl methanoate ($HCOOCH_2CH_3$).

4. The following reaction takes place: $CH_3CHCH_2(g) + H_2(g) \rightarrow CH_3CH_2CH_3(g)$
   a) Give the name of the homologous series of the organic compound in the reactants.
   b) What is the name of the homologous series of the product?
   c) Which compound in the reaction is a saturated hydrocarbon?

5. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27MC 2. 27MD 3. 27MF 4. 27MG

It is possible for two organic compounds to have the same *molecular formula* but a different *structural formula*. Look at the two organic compounds that are shown in Figure 4.44 for example.

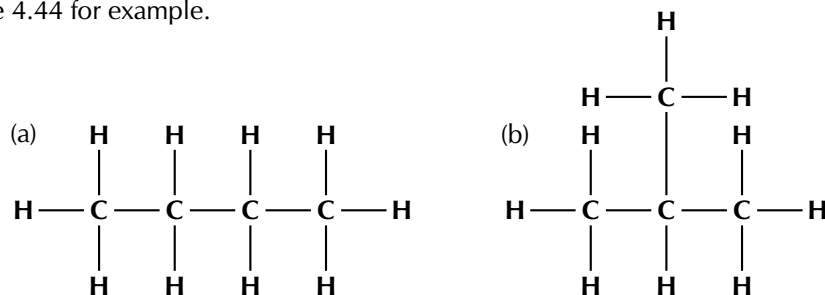



Figure 4.44: Isomers of a 4-carbon organic compound with the molecular formula $C_4H_{10}$. **(a)** butane and **(b)** 2-methylpropane.

**FACT**
Both butane and 2-methylpropane (isobutane) are used in camping stoves and lighters.

If you were to count the number of carbon and hydrogen atoms in each compound, you would find that they are the same. They both have the same molecular formula $C_4H_{10}$, but their structure is different and so are their properties. Such compounds are called **isomers**.

**DEFINITION:** *Isomer*

In chemistry, isomers are molecules with the same molecular formula but different structural formula.

Isomers are molecules with the same molecular formula and often (though not always) with the same kinds of chemical bonds between atoms, but with the atoms arranged differently.

The isomers shown in Figure 4.44 differ only in the location of the carbon atoms. The functional groups are the same but butane has all four carbons in one chain, while 2-methylpropane has three carbons in the longest chain and a methyl group attached to the second carbon in the chain. It is also possible to have *positional* isomers (Figure 4.45). In this case the −OH functional group can be on different carbon atoms, for example carbon 1 for pentan-1-ol, on carbon 2 for pentan-2-ol or on carbon 3 for pentan-3-ol.

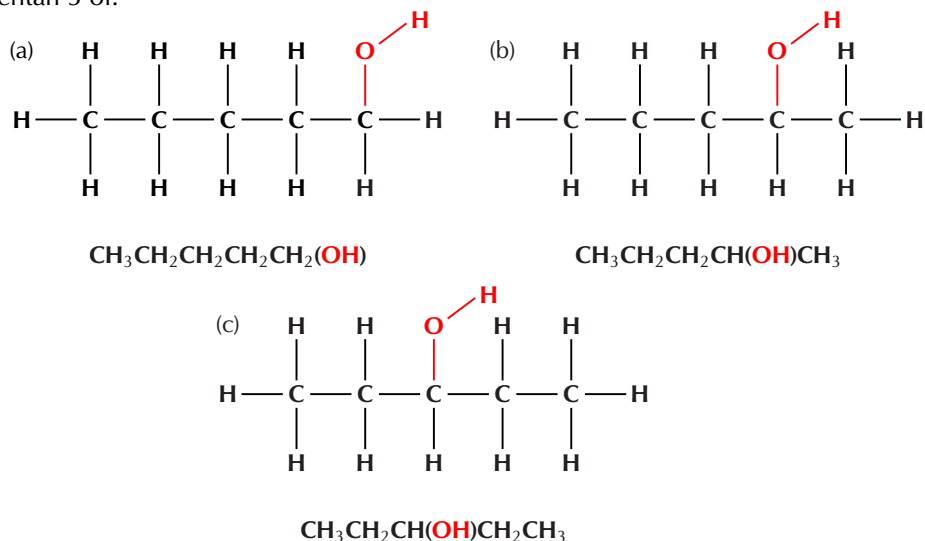



Figure 4.45: The structural and condensed structural representations of the isomers **(a)** pentan-1-ol, **(b)** pentan-2-ol and **(c)** pentan-3-ol.

Positional isomers are also found in esters. If one ester was made from ethanol and hexanoic acid and another was made from hexanol and ethanoic acid the two esters produced are isomers (see Figure 4.46).

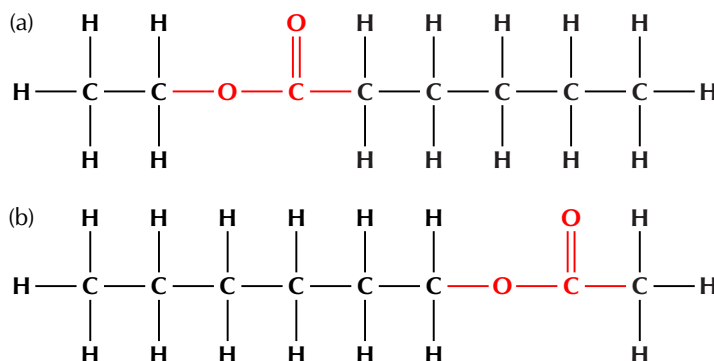



Figure 4.46: The structural representations of the isomers **(a)** ethyl hexanoate and **(b)** hexyl ethanoate.

It is important to note that molecules need not have the same functional groups to be isomers. For example propanone (commonly known as acetone) and propanal (Figure 4.47) have the same molecular formula ($C_3H_6O$) but different functional groups and properties (Table 4.3). These types of isomers are **functional isomers**.

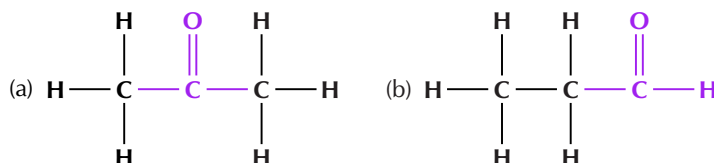



Figure 4.47: Two $C_3H_6O$ isomers **(a)** propanone and **(b)** propanal.

| Name | Functional Group | Melting point (°C) | Boiling point (°C) | Reactivity |
|---|---|---|---|---|
| propan*one* | ketone | -95 | 56 | less reactive |
| propan*al* | aldehyde | -81 | 48 | more reactive |

Table 4.3: Some properties of the isomers propanone and propanal.

Heptanoic acid and butyl propanoate (Figure 4.48) are another example of *functional* isomers (containing different functional groups). They both have the same molecular formula of $C_7H_{14}O_2$ but have different functional groups and different properties (Table 4.4).

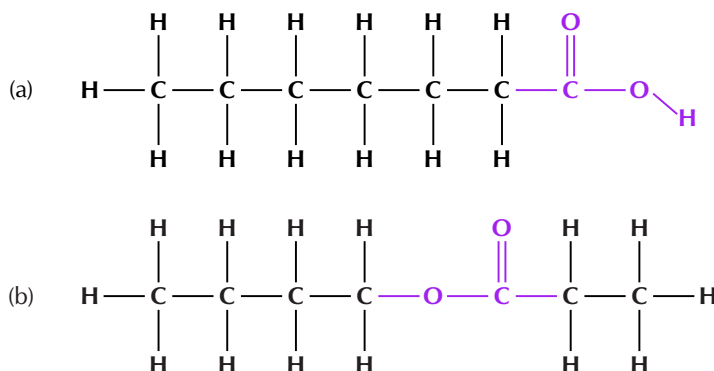



Figure 4.48: The structural representations of the isomers **(a)** heptanoic acid and **(b)** butyl propanoate.

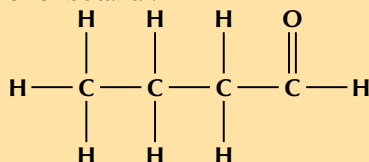
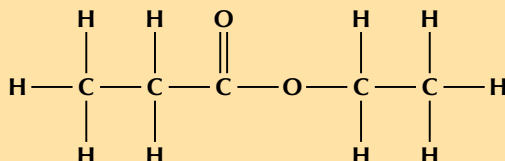
| Name | Functional group | Melting point (°C) | Boiling point (°C) |
|---|---|---|---|
| heptanoic acid | carboxylic acid | -7,5 | 223 |
| butyl propanoate | ester | -89,5 | 145 |

Table 4.4: The different physical properties of the isomers heptanoic acid and butyl propanoate.

**Exercise 4 – 7: Isomers**

1. Match the organic compound in Column A with its isomer in Column B:

| | Column A | Column B |
|---|---|---|
| 1 | $CH_3CH_2CH_2(OH)$ | $CH_3CH(CH_3)CH_3$ |
| 2 | $CH_3CH_2CH_2CH_3$ | $CH_3—CH_2—CH_2—C(=O)—CH_3$ |
| 3 | $CH_3CH_2C(=O)CH_2CH_3$ | $CH_3CH(OH)CH_3$ |

2. a) Give the ketone isomer of butanal:

b) Give a carboxylic acid that is an isomer of:

$CH_3CH_2C(=O)OCH_2CH_3$

3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27MH 2a. 27MJ 2b. 27MK

## 4.3 IUPAC naming and formulae ESCKG

### What is IUPAC naming? ESCKH

In order to give compounds a name, certain rules must be followed. When naming organic compounds, the IUPAC (International Union of Pure and Applied Chemistry) nomenclature (naming scheme) is used. This is to give consistency to the names. It also enables every compound to have a unique name, which is not possible with the common names used (for example in industry). We will first look at some of the steps

**TIP**
Molecules can contain both double or triple bonds and other functional groups (e.g. an alkene and an alcohol functional group in one molecule - prop**en**ol). However, all molecules explored in this book will contain only single carbon-carbon bonds when combined with other functional groups.

that need to be followed when naming a compound, and then try to apply these rules to some specific examples.

A good general rule to follow is to start at the **end** (the suffix) and work backwards (from right to left) in the name.

| Functional group | suffix |
|---|---|
| alkane | -ane |
| alkene | -ene |
| alkyne | -yne |
| alcohol | -ol |
| aldehyde | -al |
| ketone | -one |
| carboxylic acid | -oic acid |
| ester | -oate |

Table 4.5: The suffix associated with various functional groups.

1. Recognise the *functional group* in the compound. This will determine the suffix of the name (see Table 4.5).
2. Find the longest continuous carbon chain that contains the functional group (it won't always be a *straight* chain) and count the number of carbon atoms in this chain.
   This number will determine the prefix (the *beginning*) of the compound's name (see Table 4.6).
3. Number the carbons in the longest carbon chain (**Important:** If the molecule is not an alkane (i.e. has a functional group) you need to start numbering so that the *functional group* is on the carbon with the *lowest possible number*). Start with the carbon at the end closest to the functional group.

| Carbon atoms | prefix |
|---|---|
| 1 | meth- |
| 2 | eth- |
| 3 | prop- |
| 4 | but- |
| 5 | pent- |
| 6 | hex- |
| 7 | hept- |
| 8 | oct- |
| 9 | non- |
| 10 | dec- |

Table 4.6: The prefix of a compound's name is determined by the number of carbon atoms in the longest chain that contains the functional group.

4. Look for any branched groups:
   - Name them by counting the number of carbon atoms in the branched group and referring to Table 4.6, these groups will all end in -yl.
   - Note the position of the group on the main carbon chain. If there is more than one of the same type of branched group then both numbers must be listed (e.g. 2,4 -) and one of the prefixes listed in Table 4.7 must be used. **Important:** If the molecule is an *alkane* the branched group must be on the carbon with the *lowest possible number*.
   - The branched groups must be listed before the name of the main chain in alphabetical order (ignoring di/tri/tetra).

   If there are no branched groups this step can be ignored.

| Number | prefix |
|---|---|
| 2 | di- |
| 3 | tri- |
| 4 | tetra- |

Table 4.7: Prefixes for multiple substituents with the same name. These apply to multiple functional groups as well.

5. For the alkyl halides the halogen atom is treated in much the same way as branched groups:
   - To name them take the name of the halogen atom (e.g. iodine) and replace the -ine with -o (e.g. iodo).

- Give the halogen atom a number to show its position on the carbon chain. If there is more than one halogen atom the numbers should be listed and a prefix should be used (e.g. 3,4-diiodo- or 1,2,2-trichloro-). See Table 4.7 for a list of the prefixes.

| Halogen | name |
|---|---|
| fluorine | fluoro |
| chlorine | chloro |
| bromine | bromo |
| iodine | iodo |

Table 4.8: Naming halogen atoms in organic molecules.

- The halogen atoms must be listed before the name of the main chain in alphabetical order (ignore di/tri/tetra).

If there are no halogen atoms this step can be ignored.

6. Combine the elements of the name into a single word in the following order:
   - branched groups/halogen atoms in alphabetical order (ignoring prefixes)
   - prefix of main chain
   - name ending according to the functional group and its position on the longest carbon chain.

## Naming hydrocarbons ESCKJ

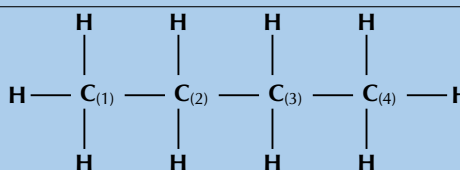
### Naming alkanes

The suffix for an alkane is -ane.

#### Worked example 1: Naming the alkanes

***QUESTION***

Give the IUPAC name for the following compound:

Note: The numbers attached to the carbon atoms would not normally be shown.
The carbon atoms have been numbered to help you to name the compound.

***SOLUTION***

**Step 1: Identify the functional group**
The compound is a hydrocarbon with single bonds between the carbon atoms. It is an alkane and will have a suffix of -ane.

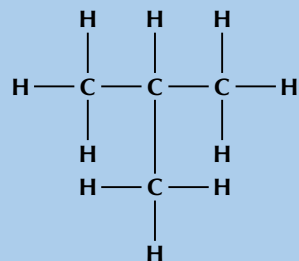
**Step 2: Find the longest carbon chain**
There are four carbon atoms in the longest chain. The prefix of the compound will be but-.

**Step 3: Number the carbon atoms in the longest chain**
The numbering has been done for you here.

**Step 4: Look for any branched group, name them and give their position on the carbon chain**
There are no branched groups in this compound.

**Step 5: Combine the elements of the name into a single word**

The name of the compound is **butane**.

## Worked example 2: Naming the alkanes

***QUESTION***

Give the IUPAC name for the following compound:

```
        H    H    H
        |    |    |
   H —  C —  C —  C — H
        |    |    |
        H    |    H
        H —  C —  H
             |
             H
```

***SOLUTION***

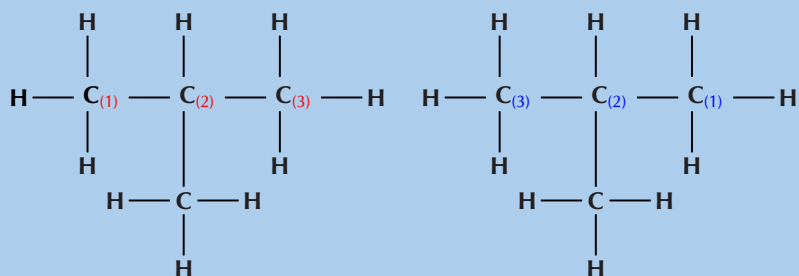
**Step 1: Identify the functional group**

The compound is a hydrocarbon with single bonds between the carbon atoms. It is an alkane and will have the suffix -ane.

**Step 2: Find the longest carbon chain**

There are three carbon atoms in the longest chain. The prefix for this compound is prop-.

**Step 3: Number the carbons in the carbon chain**

If we start at the carbon on the left, we can number the atoms as shown in red (left). If we start at the carbon on the right, we can number the atoms as shown in blue (right).

```
        H        H        H                  H        H        H
        |        |        |                  |        |        |
   H — C(1) —  C(2) —  C(3) — H         H — C(3) —  C(2) —  C(1) — H
        |        |        |                  |        |        |
        H        |        H                  H        |        H
            H —  C  — H                           H — C — H
                 |                                    |
                 H                                    H
```

**Step 4: Look for any branched groups, name them and give their position on the carbon chain**

There is a branched group attached to the second carbon atom. In this case the methyl group is on carbon 2 regardless of which side you number the longest chain from. This group has the formula $CH_3$, which is methane without a hydrogen atom. However, because it is not part of the main chain, it is given the suffix -yl (i.e. methyl). The position of the methyl group comes just before its name (see the next step).

**Step 5: Combine the elements of the compound's name into a single word in the order of branched group; prefix; name ending according to the functional group**

The compound's name is **2-methylpropane**.

## Worked example 3: Naming the alkanes

***QUESTION***

Draw the semi-structural structural and condensed structural formula for the organic compound **2,2,4-trimethylhexane**

***SOLUTION***

**Step 1: Identify the functional group**

The name ends in -ane therefore the compound is an alkane.

**Step 2: Determine the number of carbon atoms in the longest chain**

The longest chain has the prefix hex-. There are therefore 6 carbon atoms in the longest chain.

```
C — C — C — C — C — C
```

**Step 3: Look for any branched groups and place them on the structure**

The compound is **2,2,4-trimethyl**hexane. Therefore there are three branched groups. Two on carbon 2 and one on carbon 4.

```
         CH3           CH3
          |             |
C — C(2) — C — C(4) — C — C
          |
         CH3
```

**Step 4: Combine this information and add the hydrogen atoms**

Carbon atoms can have four single bonds. Therefore wherever a carbon atom has less than four bonds draw in hydrogen atoms until there are four bonds.

```
          CH3          CH3
           |            |
CH3 — C — CH2 — CH — CH2 — CH3
           |
          CH3
```

**Step 5: Condense the structural formula**

First condense the main chain: $CH_3CCH_2CHCH_2CH_3$

Then add the side chains (in brackets) on the relevant carbon atoms:

$\mathbf{CH_3C(CH_3)_2CH_2CH(CH_3)CH_2CH_3}$

## Exercise 4 – 8: Naming alkanes

1. Give the structural formula for each of the following alkanes
   a) Octane b) Propane c) 2-methylpropane d) 3-ethylpentane

2. Give the IUPAC name for each of the following alkanes:
   a) $CH_3CH_2CH(CH_3)CH_2CH_3$ b) $CH_3CH(CH_3)CH_2CH(CH_3)CH_3$
   c) $CH_3CH_2CH_2CH_2CH_2CH_3$ d) $CH_3CH_3$

e)

f)

3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27MM 2. 27MN

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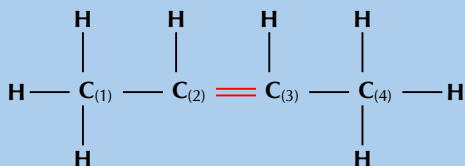
### Naming alkenes

The suffix for an alkene is -ene.

#### Worked example 4: Naming the alkenes

***QUESTION***

Give the IUPAC name for the following compound:

$$\begin{array}{ccccccccc} & & H & & H & & H & & H & & \\ & & | & & | & & | & & | & & \\ H & - & C_{(1)} & - & C_{(2)} & = & C_{(3)} & - & C_{(4)} & - & H \\ & & | & & & & & & | & & \\ & & H & & & & & & H & & \end{array}$$

***SOLUTION***

**Step 1: Identify the functional group**

The compound has a double carbon-carbon bond and is an alkene. It will have the suffix -ene.

**Step 2: Find the longest carbon chain containing the functional group**

The functional group is a double bond, so the longest chain must contain the double bond. There are four carbon atoms in the longest chain and so the prefix for this compound will be but-.

**Step 3: Number the carbon atoms**

Remember that the carbon atoms must be numbered so that the functional group is at the lowest numbered carbon atom possible. In this case, it doesn't matter whether we number the carbons from the left to right, or from the right to left. The double bond will still fall between the second and third carbon atoms.

**Step 4: Look for any branched groups, name them and give their position on the carbon chain**

There are no branched groups in this molecule.

**Step 5: Combine the elements of the name into a single word in the following order: branched groups; prefix; name ending according to the functional group and its position along the longest carbon chain**

The name of this compound is **but-2-ene** or **2-butene**.

#### Worked example 5: Naming the alkenes

***QUESTION***

Draw the structural and molecular formula for the organic compound

**3-methylbut-1-ene**

***SOLUTION***

**Step 1: Identify the functional group**

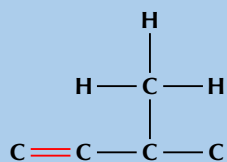
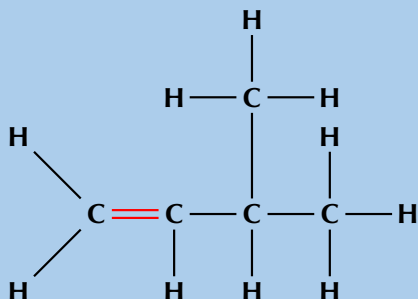
The suffix -ene means that this compound is an alkene and there must be a double bond in the molecule. The number 1 immediately before the suffix means that the double bond must be at the first carbon in the chain (but-1-ene).

**Step 2: Determine the number of carbon atoms in the longest chain containing the functional group**

The prefix for the compound is but- so there must be four carbons in the longest chain containing the double bond.

$$C = C - C - C$$

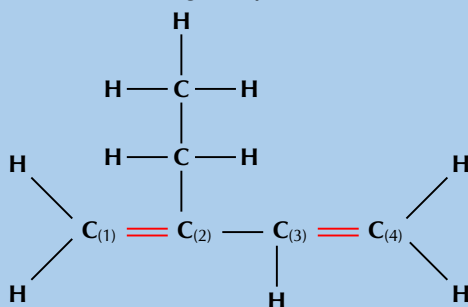
**Step 3: Look for any branched groups**

There is a methyl group at the third carbon atom in the chain. Count from the left so that the double bond carbon is the first carbon atom.

**Step 4: Combine this information and add the hydrogen atoms**

**Step 5: Reduce the structural formula to the molecular formula**

There are 5 carbon atoms and 10 hydrogen atoms so the molecular formula is $\mathbf{C_5H_{10}}$. (Remember that there is no *structural* information given by the molecular formula)

**Worked example 6: Naming the alkenes**

***QUESTION***

Give the IUPAC name for the following compound:

***SOLUTION***

**Step 1: Identify the functional group**

The compound is an alkene and will have the suffix -ene. There is a double bond between the first and second carbons and also between the third and fourth carbons. The organic compound therefore contains '1,3-diene'.

**Step 2: Find the longest carbon chain containing the functional group, and number the carbon atoms**

Remember that the main carbon chain must contain both the double bonds. There are four carbon atoms in the longest chain containing the double bonds and so the prefix for this compound will be but-. The carbon atoms are already numbered 1 to 4 in the diagram.

**Step 3: Look for any branched groups, name them and give their position on the carbon chain**

There is an ethyl group on the second carbon.

Note that if we had numbered from the right to left the suffix would still have been 1,3-diene, however the ethyl group would have been on the third carbon. So we had to number left to right.

**Step 4: Combine the elements of the name into a single word in the following order: branched groups; prefix; name ending according to the functional group and its position along the longest carbon chain**

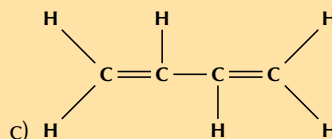
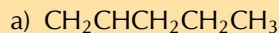
The name of this compound is **2-ethylbut-1,3-diene**.

**Exercise 4 – 9: Naming alkenes**

1. Give the IUPAC name for each of the following alkenes:

   a) $CH_2CHCH_2CH_2CH_3$

   b) $CH_3CHCHCH_3$

   c)

2. Give the structural formula for each of the following alkenes:

   a) ethene b) hex-1-ene c) hept-3-ene d) 4-ethyloct-3-ene

3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

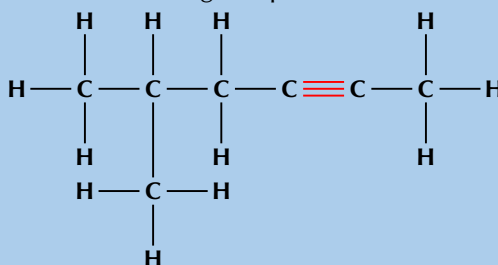
1. 27MP 2. 27MQ

**Naming alkynes**

The suffix for an alkyne is -yne.

**Worked example 7: Naming the alkynes**

***QUESTION***

Give the IUPAC name for the following compound:

***SOLUTION***

**Step 1: Identify the functional group**

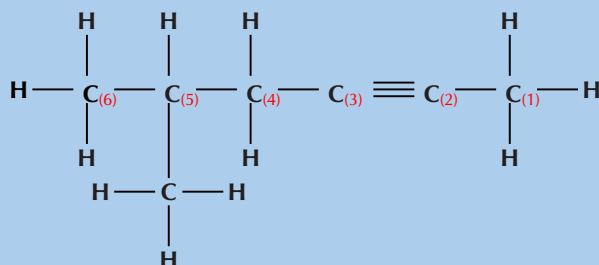
There is a triple bond between two of the carbon atoms, so this compound is an alkyne. The suffix will be -yne.

**Step 2: Find the longest carbon chain containing the functional group**

The functional group is a triple bond, so the longest chain must contain the triple bond. There are six carbon atoms in the longest chain. The prefix of the compound's name will be hex-.

**Step 3: Number the carbons in the longest chain**

In this example, you will need to number the carbons from right to left so that the triple bond is between carbon atoms with the lowest numbers (the suffix for the compound will therefore be -2-yne).

```
         H     H     H                 H
         |     |     |                 |
   H — C(6) — C(5) — C(4) — C(3) ≡ C(2) — C(1) — H
         |     |     |                 |
         H     |     H                 H
           H — C — H
               |
               H
```

**Step 4: Look for any branched groups, name them and assign the number of the carbon atom to which the group is attached**

There is a methyl ($CH_3$) group attached to the fifth carbon (remember we have numbered the carbon atoms from right to left).

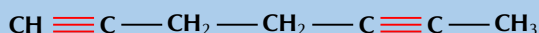
**Step 5: Combine the elements of the name into a single word in the following order: branched groups; prefix; name ending according to the functional group and its position along the longest carbon chain**

If we follow this order, the name of the compound is **5-methylhex-2-yne**.

**Worked example 8: Naming the alkynes**

***QUESTION***

Give the IUPAC name for the following compound:

$$CH \equiv C - CH_2 - CH_2 - C \equiv C - CH_3$$

***SOLUTION***

**Step 1: Identify the functional group**

There are two triple bonds. The suffix will therefore be -diyne.

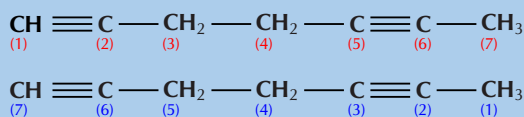
**Step 2: Find the longest carbon chain containing the functional group**

The functional group is a triple bond, so the longest chain must contain all triple bonds. The longest carbon chain contains seven carbon atoms, therefore the prefix will be hept-.

**Step 3: Number the carbons in the longest chain**

Numbering from left to right (shown in red) the first triple bond is on carbon 1 and the second is on carbon 5. The suffix will therefore be -1,5-diyne.

$$\underset{(1)}{CH} \equiv \underset{(2)}{C} - \underset{(3)}{CH_2} - \underset{(4)}{CH_2} - \underset{(5)}{C} \equiv \underset{(6)}{C} - \underset{(7)}{CH_3}$$

$$\underset{(7)}{CH} \equiv \underset{(6)}{C} - \underset{(5)}{CH_2} - \underset{(4)}{CH_2} - \underset{(3)}{C} \equiv \underset{(2)}{C} - \underset{(1)}{CH_3}$$

(Numbering from right to left (shown in blue) will give the suffix -2,6-diyne, and is incorrect).

**Step 4: Look for any branched groups**

There are no branched groups for this molecule.

**Step 5: Combine the elements of the name into a single word in the following order: branched groups; prefix; name ending according to the functional group and its position along the longest carbon chain**

The name of the compound is **hept-1,5-diyne**.

### Worked example 9: Naming the alkynes

***QUESTION***

Draw the structural and condensed structural formula for the organic compound **6-methylhept-3-yne**

***SOLUTION***

**Step 1: Identify the functional group**

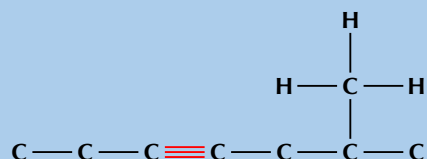
The suffix -3-yne means that this compound is an alkyne and there must be a triple bond located on carbon number 3.

**Step 2: Determine the number of carbon atoms in the longest chain containing the functional group**

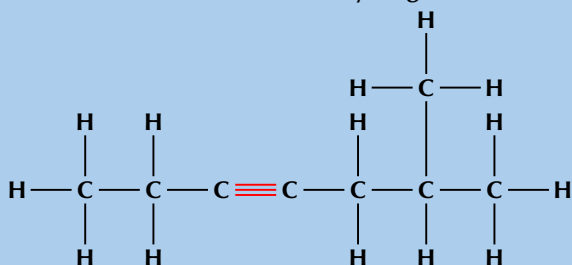
The prefix for the compound is hept- so there must be seven carbons in the longest chain.

```
C — C — C ≡ C — C — C — C
```

**Step 3: Look for any branched groups**

There is a methyl group located on carbon number 6.

```
                        H
                        |
                    H — C — H
                        |
C — C — C ≡ C — C — C — C
```

**Step 4: Combine this information and add the hydrogen atoms**

```
                              H
                              |
                          H — C — H
        H   H             H   |   H
        |   |             |   |   |
    H — C — C — C ≡ C — C — C — C — H
        |   |             |   |   |
        H   H             H   H   H
```

**Step 5: Condense the structural formula**

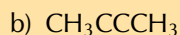
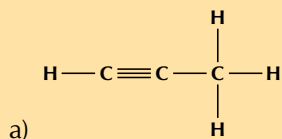
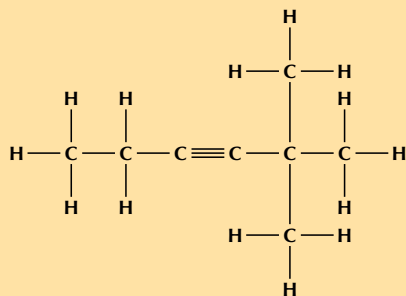
First condense the main chain: $CH_3CH_2CCCH_2CHCH_3$

Then add the side chains (in brackets) on the relevant carbon atoms:

$\mathbf{CH_3CH_2CCCH_2CH(CH_3)CH_3}$

### Exercise 4 – 10: Naming alkynes

1. Give the structural formula for each of the following alkynes:
   a) ethyne  b) pent-1-yne  c) 5-methylhept-3-yne

2. Give the IUPAC names for the following alkynes:

a)
```
                H
                |
H — C ≡ C — C — H
                |
                H
```

b) $CH_3CCCH_3$

c) 

3. More questions. Sign in at Everything Science online and click 'Practise Science'.

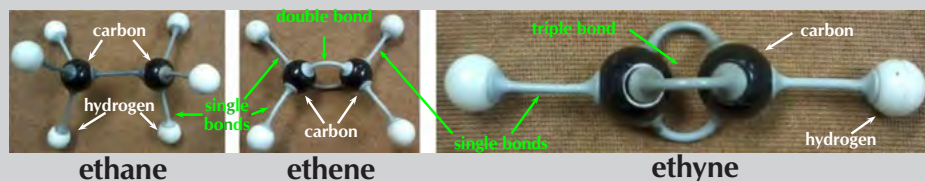
Check answers online with the exercise code below or click on 'show me the answer'.

1. 27MR    2. 27MS

 www.everythingscience.co.za     m.everythingscience.co.za

**Activity: Building hydrocarbons**

An example of ethane, ethene and ethyne built with atomic model kits is given in the picture below:

ethane    ethene    ethyne

1. Using atomic model kits, build the molecules of methane, propane, butane, pentane and octane. If you don't have atomic model kits, jelly tots (or playdough) and toothpicks will work just as well. Use one colour jelly tot for the carbon atoms and one for the hydrogen atoms.
    - Remember that carbon atoms should have four bonds and hydrogen atoms can have only one. You should see that all these compounds have a similar formula, remember they all have the general formula $C_nH_{2n+2}$.
    - What is the name of the homologous series that all these molecules belong to?

2. Build the molecules of prop-1-ene, but-1-ene, pent-1-ene and oct-1-ene. Use two toothpicks to represent a double bond. You should see that all these compounds have a similar formula. Remember, they all have the general formula $C_nH_{2n}$.
    - Try placing the double bond at different positions within the molecule. Does this make any difference to the total number of carbon and hydrogen atoms in the molecule?
    - What is the name of the homologous series that all these molecules belong to?

3. Build the molecules of prop-1-yne, but-1-yne, pent-1-yne and oct-1-yne. Use three toothpicks to represent a triple bond. You should see that all these compounds have a similar formula. Remember, they are all alkynes.
    - Try placing the triple bond at different positions within the molecule. Does this make any difference to the total number of carbon and hydrogen atoms in the molecule?
    - What is the general formula for the alkynes?

**Exercise 4 – 11: Naming hydrocarbons**

1. Give the structural formula for each of the following compounds:

   a) oct-2-ene  b) 3-methylhexane  c) 4-ethyl-4-methylhept-2-yne
   d) hept-3-yne  e) pentane  f) 2-methylbut-1-ene  g) propyne

2. Give the IUPAC name for each of the following organic compounds:

a)  b)

c) $CH_3CH_2CH_2CH_2CH_2CH_3$   d) $CH_3CH_2CCH$

e)   f) $C_2H_2$   g) $CH_3CHCH_2$

3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27MT  2. 27MV

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## Naming alkyl halides

ESCKK

All the same rules apply when naming the alkyl halides as for naming the hydrocarbons. We will only be dealing with the haloalkanes (i.e. there are no other functional groups). The halogen atom is treated in the same way as a branched group.

**Worked example 10: Naming the haloalkanes**

***QUESTION***

Give the IUPAC name for the following compound:

***SOLUTION***

**Step 1: Identify the functional group**

There is a halogen atom and no other functional group. This compound is therefore a haloalkane, and will have the suffix -ane.

**Step 2: Find the longest carbon chain containing the functional group**

There are three carbons in the longest chain containing the halogen atom. The prefix is prop-.

**Step 3: Number the carbon atoms in the longest chain**

You need to number the carbon atoms so that the halogen atom is on the carbon atom

with the lowest number. In this case you can number from either side.

**Step 4: Name the halogen atom and assign the number for the carbon atom it is attached to**

The halogen is a chlorine atom. It is attached to carbon number 2 and so will have the name 2-chloro.

**Step 5: Look for branched groups**

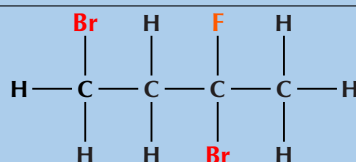
There are no branched groups in this compound.

**Step 6: Combine the elements of the name into a single word in the following order: halogen atoms; prefix; name ending according to functional group**

The name of the compound is **2-chloropropane**.

**Worked example 11: Naming the haloalkanes**

***QUESTION***

Give the IUPAC name for the following compound:

***SOLUTION***

**Step 1: Identify the functional group**

There are three halogen atoms and no other functional groups. This compound is therefore a haloalkane, and will have the suffix -ane.

**Step 2: Find the longest carbon chain containing the functional group**

There are four carbons in the longest chain containing all the halogen atoms. The prefix for this compound will be but-.

**Step 3: Number the carbon atoms in the longest chain**

You need to number the carbon atoms so that the halogen atoms are on the carbon atoms with the lowest numbers. You must number from left to right here so that one halogen atom is on carbon 1 and two halogen atoms are on carbon 3.

**Step 4: Name the halogen atoms and assign the number for the carbon atom attached to it**

There are two halogen atoms that are bromine atoms and one that is fluorine. One bromine is attached to carbon 1 and one is attached to carbon 3. The fluorine atom is attached to carbon 3. So you have 1,3-dibromo- and 3-fluoro.

**Step 5: Look for branched groups**

There are no branched groups in this compound.

**Step 6: Combine the elements of the name into a single word in the following order: halogen atoms in alphabetical order; prefix; name ending according to functional group**

The name of the compound is **1,3-dibromo-3-fluorobutane**. Note that we place the halogens in alphabetical order: *b*romo (ignore the di/tri/tetra) is before *f*luoro.

**Worked example 12: Naming the haloalkanes**

***QUESTION***

Draw the structural and condensed structural formula for the organic compound **2-iodo-3-methylpentane**

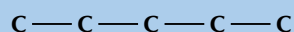
***SOLUTION***

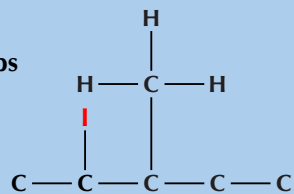
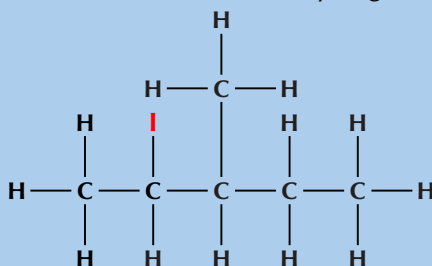
**Step 1: Identify the functional group**

This compound has the suffix -ane, but also contains a halogen atom. It is therefore a haloalkane. Note that the methyl and iodo are written in alphabetical order.

**Step 2: Find the longest carbon chain containing the functional group**

The prefix is pent- therefore there are 5 carbons in the longest chain.

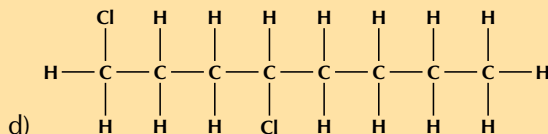
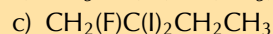
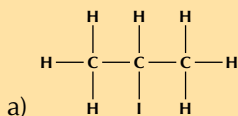
C — C — C — C — C

**Step 3: Place the halogen atom(s) and any branched groups**

There is an iodine atom on the second carbon atom, and a methyl branched group on the third carbon atom.

**Step 4: Combine this information to and add the hydrogen atoms**

**Step 5: Condense the structural formula**

First condense the main chain: $CH_3CHCHCH_2CH_3$

Then add the side chains and halogen atoms (in brackets) on the relevant carbon atoms: $\mathbf{CH_3CH(I)CH(CH_3)CH_2CH_3}$

**Exercise 4 – 12: Naming haloalkanes**

1. Give the structural representation for the following haloalkanes:
   a) 2-chlorobutane  b) 1-bromopropane  c) 2,3-difluoropentane
2. Give the IUPAC name for the following haloalkanes:

   b) $CH_3CH(Br)CH(CH_3)CH_2CH_2CH_3$
   c) $CH_2(F)C(I)_2CH_2CH_3$

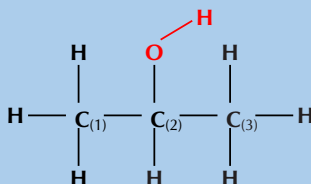
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27MW  2. 27MX

## Naming alcohols ESCKM

The rules used to name the alcohols are similar to those already discussed for the hydrocarbons. The suffix of an alcohol is –ol (see Table 4.5).

### Worked example 13: Naming the alcohols

***QUESTION***

Give the IUPAC name for the following organic compound

```
              H
             /
    H    O       H
    |    |       |
H — C(1)— C(2)— C(3)— H
    |    |       |
    H    H       H
```

***SOLUTION***

**Step 1: Identify the functional group**

The compound has an –OH (hydroxyl) functional group and is therefore an alcohol. The compound will have the suffix -ol.

**Step 2: Find the longest carbon chain containing the functional group**

There are three carbon atoms in the longest chain that contains the functional group. The prefix for this compound will be prop-. As there are only single bonds between the carbon atoms, the prefix includes *an* to become propan-.

**Step 3: Number the carbons in the carbon chain**

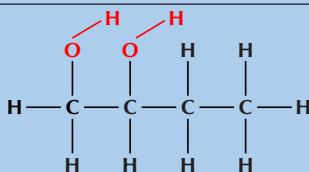
In this case, it doesn't matter whether you start numbering from the left or right. The hydroxyl group will still be attached to second carbon atom (-2-ol).

**Step 4: Look for branched groups**

There are no branched groups in this compound.

**Step 5: Combine the elements of the compound's name into a single word in the order of branched groups; prefix; name ending according to the functional group**

The compound's name is **propan-2-ol** or **2-propanol**.

### Worked example 14: Naming the alcohols

***QUESTION***

Give the IUPAC name for the following compound:

```
     H    H
    /    /
    O    O    H    H
    |    |    |    |
H — C —  C —  C —  C — H
    |    |    |    |
    H    H    H    H
```

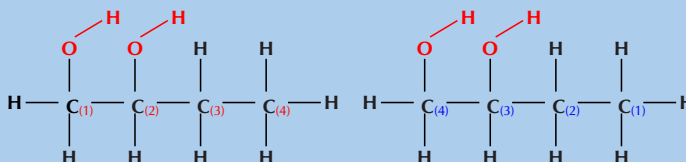
***SOLUTION***

**Step 1: Identify the functional group**

The compound has an –OH (hydroxyl) functional group and is therefore an alcohol. There are *two* hydroxyl groups in the compound, so the suffix will be -diol.

**Step 2: Find the longest carbon chain that contains the functional group**

There are four carbon atoms in the longest chain that contains the functional group (but-) and only single bonds (an-). The prefix for this compound will be butan-.

**Step 3: Number the carbons in the carbon chain**

There are two hydroxyl groups attached to the main chain. If we number as shown in red (on the left) they are attached to the first and second carbon atoms. If we number as shown in blue (on the right) they are attached to the third and fourth carbon atoms.

The functional groups should have the lowest numbers possible. Therefore the red numbering is correct. The hydroxyl groups are attached to the first and second carbon atoms (1,2-diol).

**Step 4: Look for branched groups**

There are no branched groups in this compound.

**Step 5: Combine the elements of the compound's name into a single word in the order of branched groups; prefix; name ending according to the functional group**

The compound's name is **butan-1,2-diol**.

### Worked example 15: Naming the alcohols

***QUESTION***

Draw the structural and condensed structural representations for the organic compound **4-ethyloctan-2,5-diol**

***SOLUTION***

**Step 1: Identify the functional group**

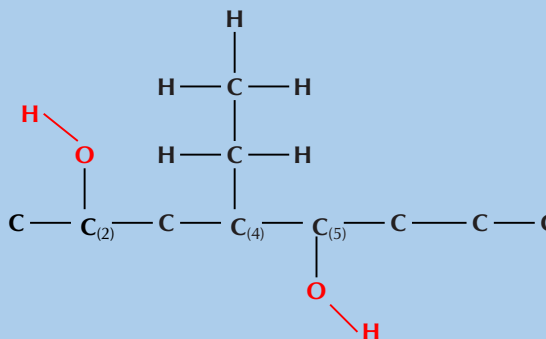
The compound has the suffix -ol. It is therefore an alcohol.

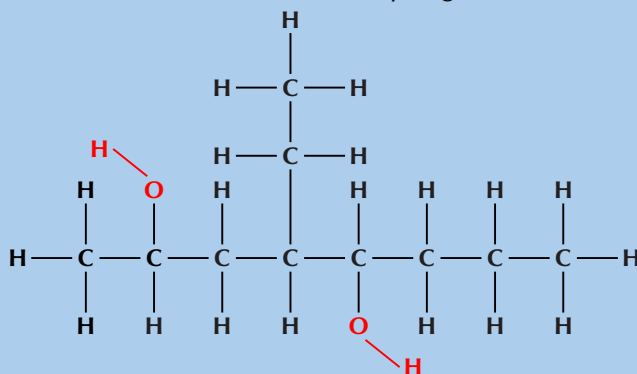
**Step 2: Find the longest carbon chain that contains the functional group**

The prefix is oct- therefore there are 8 carbons in the longest chain containing the functional group.

C — C — C — C — C — C — C — C

**Step 3: Place the functional group as well as any branched groups**

There is one −OH attached to carbon 2 and one attached to carbon 5. There is also an ethyl ($-CH_2CH_3$) branched group attached to carbon 4.

**Step 4: Combine this information and add the hydrogen atoms**

```
                      H
                      |
                  H — C — H
                      |
      H           H — C — H
       \              |
    H    O      H     |     H     H     H     H
    |    |      |     |     |     |     |     |
H — C —  C  —   C  —  C  —  C  —  C  —  C  —  C — H
    |    |      |     |     |     |     |     |
    H    H      H     H     O     H     H     H
                             \
                              H
```

**Step 5: Condense the structural formula**

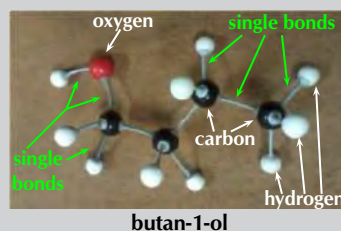
First condense the main chain: $CH_3CHCH_2CHCHCH_2CH_2CH_3$

Then add the side chains and alcohol functional groups (in brackets) on the relevant carbon atoms: $\mathbf{CH_3CH(OH)CH_2CH(CH_2CH_3)CH(OH)CH_2CH_2CH_3}$

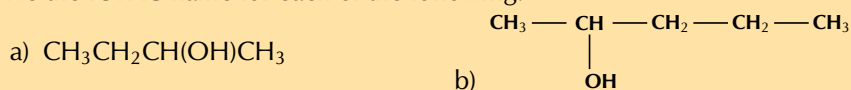
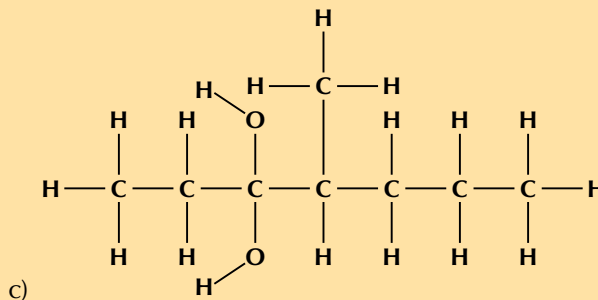
**Activity: Building alcohols**

The structural representation of butan-1-ol built using an atomic model kit is given below:

Using atomic model kits, build the molecules of methanol, ethanol, propan-1-ol, pentan-1-ol and octan-1-ol. If you don't have an atomic model kit remember that you can use jelly tots (or playdough) and toothpicks. Use different colour jelly tots to represent the different atoms.

**butan-1-ol**

- You should see that all these compounds have a similar formula. Remember, they belong to the homologous series of the alcohols. What is the general formula for this series?
- Try placing the hydroxyl group at different positions within the molecule. Does this make any difference to the total number of carbon, hydrogen and oxygen atoms in the molecule?

**Exercise 4 – 13: Naming alcohols**

1. Give the structural representation of each of the following organic compounds:
   a) pentan-3-ol  b) butan-2,3-diol  c) 2-methylpropan-1-ol
2. Give the IUPAC name for each of the following:
   a) $CH_3CH_2CH(OH)CH_3$
   b)

```
CH3 — CH — CH2 — CH2 — CH3
      |
      OH
```

c) 

3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27MY  2. 27MZ

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## Naming carbonyl compounds  ESCKN

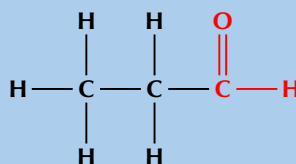
A carbonyl group consists of a carbon atom that is bonded to an oxygen atom through a double bond (C=O). There are many different functional groups that contain a carbonyl group.

### Naming aldehydes

If the carbonyl group is on the *end* of the carbon chain, the organic compound is called an *aldehyde*. An aldehyde has the suffix -al.

**Worked example 16: Naming aldehydes**

***QUESTION***

Give the IUPAC name and molecular formula for the following organic compound

***SOLUTION***

**Step 1: Identify the functional group**

The compound has a C=O (carbonyl) group and no other functional groups. It is therefore either an aldehyde or a ketone. The carbonyl group is on the last (terminal) carbon in the main chain so the compound is an aldehyde. It will have the suffix -al.

**Step 2: Find the longest carbon chain containing the functional group**

There are three carbons in the longest chain that contains the functional group. The prefix for this compound will be prop-. As there are only single bonds between the carbon atoms, the prefix becomes propan-.

**Step 3: Number the carbon atoms in the carbon chain**

The carbon atoms will be numbered so that the carbon atom of the aldehyde group has the lowest number possible. In this case that is from right to left.

**Step 4: Look for any branched groups**

There are no branched groups in this compound.

**Step 5: Combine the elements of the compound's name into a single word in the order of branched groups; prefix; name ending according to the functional group**

The compound's name is **propanal** (there is no need to say propan-1-al as by definition all aldehydes are -1-al).

**Step 6: Reduce the structural representation to the molecular formula**

There are 3 carbon atoms, 6 hydrogen atoms and 1 oxygen atom so the molecular formula is $\mathbf{C_3H_6O}$.

(Remember that there is no *structural* information given by the molecular formula)

**TIP**

Ketone is pronounced *key***tone**. Therefore propanone is pronounced propan**own**.

**FACT**

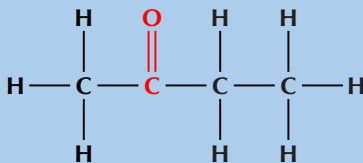
Note that butanone can only be butan-2-one. If the carbonyl group were on carbon 1 it would be an aldehyde, while if it were on carbon 3 we would simply count from the other side of the molecule. The 2 is still required for IUPAC naming however.

### Naming ketones

If the carbonyl group is in the middle of the carbon chain, the compound is called a *ketone*. A ketone has the suffix -one.

**Worked example 17: Naming ketones**

***QUESTION***

Give the IUPAC name and molecular formula for the following compound:

```
    H   O   H   H
    |   ‖   |   |
H — C — C — C — C — H
    |       |   |
    H       H   H
```

***SOLUTION***

**Step 1: Identify the functional group**

The compound has a C=O (carbonyl) group and no other functional groups. It is therefore either an aldehyde or a ketone. The carbonyl group is **not** at the end of the chain. Therefore the compound is a ketone and the suffix will be -one.

**Step 2: Find the longest carbon chain containing the functional group**

There are four carbons in the longest chain that contains the functional group, and only single carbon-carbon bonds. The prefix for this compound will be butan-.

**Step 3: Number the carbon atoms in the carbon chain**

The carbon atoms will be numbered from left to right so that the carbon atom of the ketone group has the lowest number possible (-2-one).

**Step 4: Look for any branched groups**

There are no branched groups in this compound.

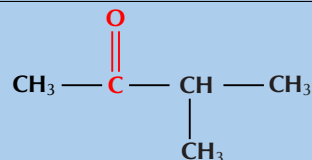
**Step 5: Combine the elements of the compound's name into a single word in the order of branched groups; prefix, name ending according to the functional group**

The compound's name is **butan-2-one** or **2-butanone**.

**Step 6: Reduce the structural representation to the molecular formula**

There are 4 carbon atoms, 8 hydrogen atoms and 1 oxygen atom so the molecular formula is $\mathbf{C_4H_8O}$.

(Remember that there is no *structural* information given by the molecular formula)

**Worked example 18: Naming carbonyl compounds**

***QUESTION***

Give the IUPAC name for the following compound:

```
             O
             ‖
CH3 —— C —— CH —— CH3
                  |
                  CH3
```

***SOLUTION***

**Step 1: Identify the functional group**

The compound has a C=O (carbonyl) group and no other functional groups. It is therefore either an aldehyde or a ketone. The carbonyl group is **not** at the end of the chain. Therefore the compound is a ketone and the suffix will be -one.

**Step 2: Find the longest carbon chain that contains the functional group**

The longest carbon chain that contains the functional group has four carbon atoms in it, and only single bonds. The prefix for this compound will be butan-.

**Step 3: Number the carbon atoms in the carbon chain**

The carbon atoms will be numbered from left to right so that the carbon atom of the ketone functional group has the lowest possible number. The suffix will be -2-one.

**Step 4: Look for any branched groups**

There is a branched group on carbon 3. This group has only one carbon atom. The branched group is attached to the third carbon atom (3-methyl).

**Step 5: Combine the elements of the compound's name into a single word in the order of branched groups; prefix; name ending according to the functional group**

The compound's name is **3-methylbutan-2-one**.

**Worked example 19: Naming carbonyl compounds**

***QUESTION***

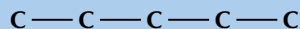
Draw the structural and condensed structural representations for the organic compound **3-methylpentanal**.

***SOLUTION***

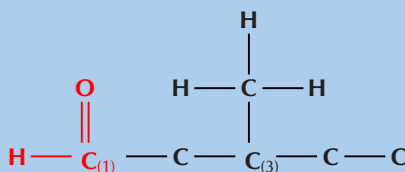
**Step 1: Identify the functional group**

The compound has the suffix -al. It is therefore an aldehyde and has a C=O (carbonyl) group on the first carbon atom.

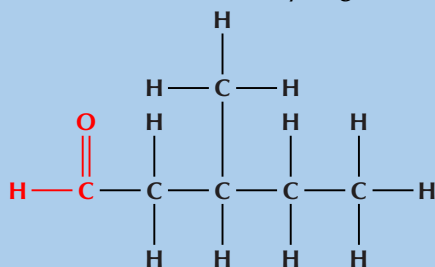
**Step 2: Find the longest carbon chain that contains the functional group**

The prefix is pent- so there are 5 carbon atoms in the longest chain.

C — C — C — C — C

**Step 3: Place the functional group as well as any branched groups**

There is a C=O (carbonyl) group at the first carbon atom and a methyl group attached to the third carbon atom (3-methyl).

```
                    H
                    |
       O        H — C — H
       ‖            |
H — C(1) — C — C(3) — C — C
```

**Step 4: Combine this information and add the hydrogen atoms**

```
               H
               |
           H — C — H
     O     H   |   H   H
     ||    |   |   |   |
 H — C  —  C — C — C — C — H
           |   |   |   |
           H   H   H   H
```

**Step 5: Condense the structural representation**

First condense the main chain including the carbonyl group oxygen atom: $CHOCH_2CHCH_2CH_3$

Then add the side chains on the relevant carbon atoms: **$CHOCH_2CH(CH_3)CH_2CH_3$**

**Worked example 20: Naming carbonyl compounds**

***QUESTION***

Draw the structural and condensed structural representations for the organic compound **3-methylpentan-2-one**.

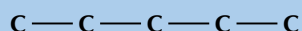
***SOLUTION***

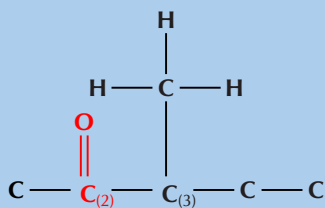
**Step 1: Identify the functional group**

The compound has the suffix -one. It is therefore a ketone and has a C=O (carbonyl) group. This group *cannot* be on the first carbon atom.

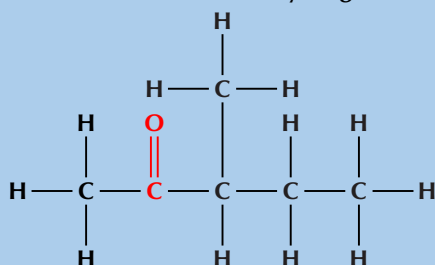
**Step 2: Find the longest carbon chain that contains the functional group**

The prefix is pent- therefore there are 5 carbon atoms in the longest chain.

```
C — C — C — C — C
```

**Step 3: Place the functional group as well as any branched groups**

There is a C=O (carbonyl) group at the second carbon atom (-2-one) and a methyl group attached to the third carbon atom (3-methyl).

```
                  H
                  |
              H — C — H
        O         |
        ||        |
C —  C(2)  —  C(3) — C — C
```

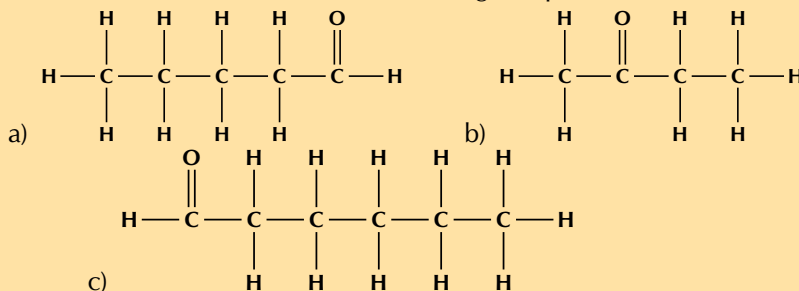
**Step 4: Combine this information and add the hydrogen atoms**

```
               H
               |
           H — C — H
     H   O     |   H   H
     |   ||    |   |   |
 H — C — C  —  C — C — C — H
     |         |   |   |
     H         H   H   H
```

**Step 5: Condense the structural representation**

First condense the main chain including the carbonyl group oxygen atom: $CH_3COCHCH_2CH_3$

Then add the side chains on the relevant carbon atoms: $\mathbf{CH_3COCH(CH_3)CH_2CH_3}$

**Exercise 4 – 14: Naming aldehydes and ketones**

1. Give the IUPAC name for each of the following compounds:

   d) HCHO    e) $CH_3CH_2COCH_2CH_3$

2. Give the structural representation for the following:

   a) ethanal    b) propanone    c) heptan-3-one

3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

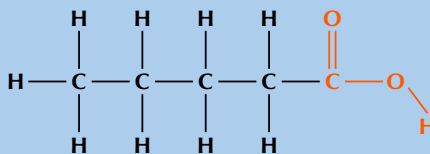
1. 27N2  2. 27N3

### Naming carboxylic acids

Carboxylic acids are characterised by having a carboxyl group, which has the formula $-COOH$. In a carboxyl group a carbon atom is double-bonded to an oxygen atom (a carbonyl group), and is also bonded to a hydroxyl (alcohol) group. The IUPAC suffix for a carboxylic acid is -oic acid.

**Worked example 21: Naming carboxylic acids**

***QUESTION***

Give the IUPAC name and molecular formula for the following compound:

***SOLUTION***

**Step 1: Identify the functional group**

The compound has a $-COOH$ group and is therefore a carboxylic acid. The suffix will be -oic acid.

**Step 2: Find the longest carbon chain that contains the functional group**

There are five carbon atoms in the longest chain that contains the functional group, and only single bonds between carbon atoms. The prefix for this compound is pentan-.

**Step 3: Number the carbon atoms in the carbon chain**

The carbon atoms will be numbered from right to left so that the carboxylic acid functional group has the lowest numbered carbon atom.

**Step 4: Look for any branched groups**

There are no branched groups in this compound.

**Step 5: Combine the elements of the compound's name into a single word in the order of branched groups; prefix, name ending according to the functional group**

The compound's name is **pentanoic acid**.

**Step 6: Reduce the structural representation to the molecular formula**

There are 5 carbon atoms, 10 hydrogen atoms and 2 oxygen atoms so the molecular formula is $\mathbf{C_5H_{10}O_2}$.

### Worked example 22: Naming carboxylic acids

***QUESTION***

Draw the structural and condensed structural representations for the organic compound **2-ethylhexanoic acid**.

***SOLUTION***

**Step 1: Identify the functional group**

The compound has the suffix -oic acid. It is therefore a carboxylic acid and has a −COOH group. This group can only be on carbon 1 (at the end of the carbon chain).

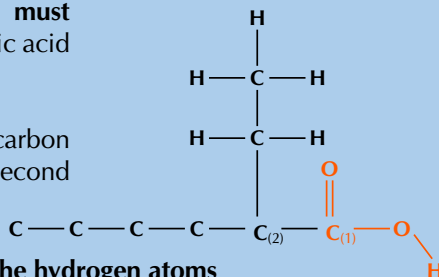
**Step 2: Find the longest carbon chain that contains the functional group**

The prefix is hex- therefore there are 6 carbons in the longest chain.

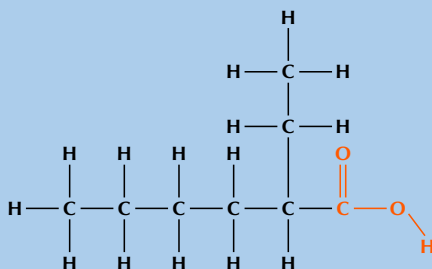
C — C — C — C — C — C

**Step 3: Place the functional group as well as any branched groups**

Remember that the main carbon chain **must** contain the functional group. This is hexanoic acid and **not** a substituted heptane.

The −COOH group contains the first carbon atom. The ethyl group is attached to the second carbon atom.

```
                          H
                          |
                      H — C — H
                          |
                      H — C — H
                          |        O
                          |        ‖
C — C — C — C — C(2) — C(1) — O
                                    \
                                     H
```

**Step 4: Combine this information and add the hydrogen atoms**

```
                          H
                          |
                      H — C — H
                          |
                      H — C — H
      H   H   H   H       |   O
      |   |   |   |       |   ‖
  H — C — C — C — C — C — C — O
      |   |   |   |   |        \
      H   H   H   H   H         H
```

**Step 5: Condense the structural representation**

First condense the main chain, including the $-COOH$ functional group:

$CH_3CH_2CH_2CH_2CHCOOH$

Then add the side chains (in brackets) on the relevant carbon atoms:

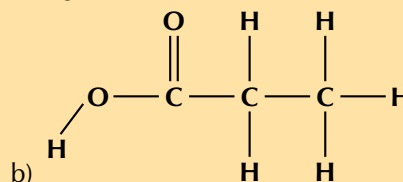
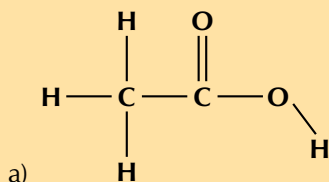
$\mathbf{CH_3CH_2CH_2CH_2CH(CH_2CH_3)COOH}$

**Activity: Building carboxylic acids**

Using atomic model kits build the molecules of methanoic acid, ethanoic acid, butanoic acid, pentanoic acid and octanoic acid. If you don't have an atomic model kit remember that you can use jelly tots (or playdough) and toothpicks. Use different colour jelly tots to represent the different atoms and two toothpicks to represent double bonds.

- You should see that all these compounds have a similar formula. Remember, they belong to the carboxylic acid homologous series. What is the general formula for this series?
- Remember that carbon must have four bonds, oxygen must have two bonds and hydrogen can only have one bond. Thinking about this fact, is it possible to have the carboxylic acid ($-COOH$) group in a position other than the last (or first) carbon atom?

**Exercise 4 – 15: Naming carboxylic acids**

1. Give the structural representation for the following:
   a) pentanoic acid
   b) 4-ethyl-7-methyloctanoic acid
   c) 4,4-diethylheptanoic acid
2. Give the IUPAC name for each of the following:

   c) $CH_3C(CH_3)_2CH_2CH_2COOH$
   d) $CH_3CH_2CH_2CH(CH_2CH_3)CH_2CH(CH_2CH_3)COOH$
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27N4 2. 27N5

**Naming esters**

When an alcohol reacts with a carboxylic acid an *ester* is formed. A new bond is formed between the oxygen atom of the hydroxyl group and the carbonyl carbon atom of the carboxylic acid. The suffix for an ester is -oate.

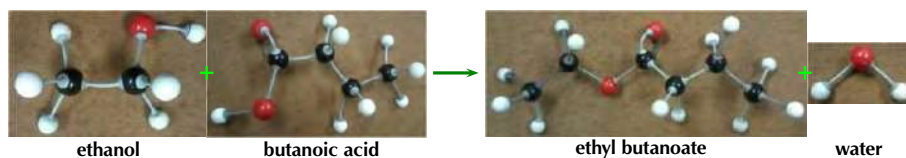



Figure 4.49: The esterification process of ethanol and butanoic acid to ethyl butanoate and water.

(a)

```
     H   H       O   H   H   H
     |   |       ||  |   |   |
 H — C — C — O — C — C — C — C — H
     |   |           |   |   |
     H   H           H   H   H
```

(b) $CH_3CH_2CH_2COOCH_2CH_3$ (c) $C_6H_{12}O_2$

(d)

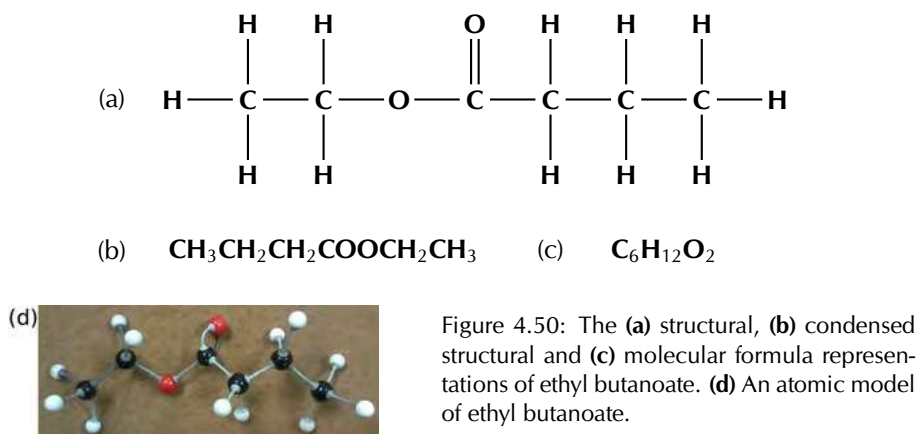



Figure 4.50: The **(a)** structural, **(b)** condensed structural and **(c)** molecular formula representations of ethyl butanoate. **(d)** An atomic model of ethyl butanoate.

Although the part of the ester from the alcohol (ethyl) is on the right, and the part from the carboxylic acid (butan-) is on the left in Figure 4.51, when naming the structure the part of the name from the alcohol is written first (ethyl butanoate). Don't forget to count the carbon atom in the carbonyl group when determining the number of carbon atoms in the chain.

(a)

```
     H   H   H   O       H   H
     |   |   |   ||      |   |
 H — C — C — C — C — O — C — C — H
     |   |   |           |   |
     H   H   H           H   H
```

(b)

```
                            O
                            ||
 CH3 — CH2 — CH2 — C — O — CH2 — CH3
```

(b) $CH_3 — CH_2 — CH_2 — C(=O) — O — CH_2 — CH_3$

(c) $CH_3CH_2CH_2COOCH_2CH_3$

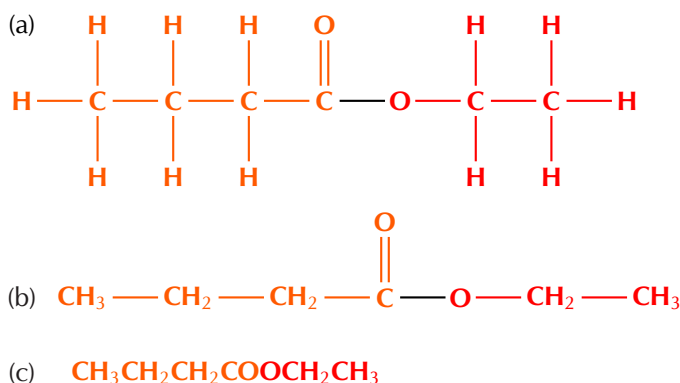
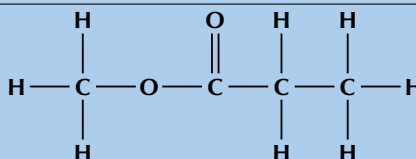



Figure 4.51: The **(a)** structural, **(b)** semi-structural structural and **(c)** condensed structural representations of ethyl butanoate.

## Worked example 23: Naming esters

### *QUESTION*

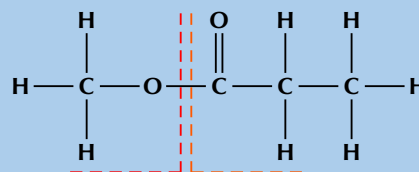
Give the IUPAC name for the following compound:

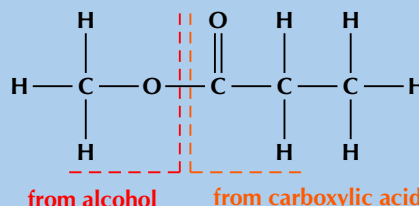
```
     H       O   H   H
     |       ||  |   |
 H — C — O — C — C — C — H
     |           |   |
     H           H   H
```

### *SOLUTION*

**Step 1: Identify the functional group**

There is a −C=O (carbonyl) group as well as an oxygen atom bonded to the carbon atom of the carbonyl and another carbon atom. This is therefore an ester and the suffix is -oate.

**Step 2: Determine which part is from the alcohol and which is from the carboxylic acid**

An ester is a carboxylic acid derivative. Divide the molecule in two with the carbonyl group on one side and the oxygen bonded to two carbon atoms on the other.

The part containing the oxygen atom bonded to two different carbon atoms was formed from the alcohol and is on the left here. The part containing the carbonyl group was formed from the carboxylic acid and is on the right here.

from alcohol    from carboxylic acid

**Step 3: Number the carbon atoms on the carbon chains**

There is only one carbon atom in the left-hand chain (from the alcohol). Therefore this will be methyl. There are three carbon atoms in the right-hand chain (from the carboxylic acid) therefore the prefix will be propan-.

**Step 4: Combine the elements of the compound's name into a single word in the order of chain from the alcohol; prefix (from chain containing carbonyl functional group), name ending according to functional group**

The compound's name is **methyl propanoate**.

**Worked example 24: Naming esters**

***QUESTION***

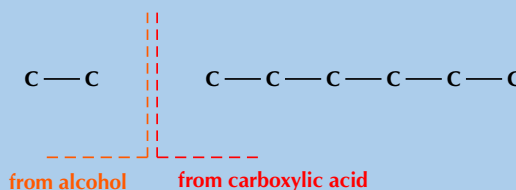
Draw the structural and condensed structural representations for the organic compound **ethyl hexanoate**.

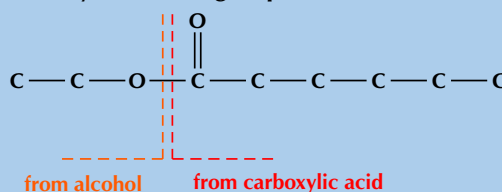
***SOLUTION***

**Step 1: Identify the functional group**

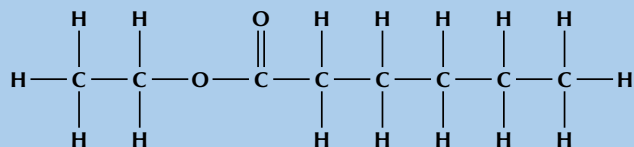
The compound has the suffix -oate. It is therefore an ester and has a $-C=O$ (carbonyl) group as well as an oxygen atom bonded to the carbon atom of the carbonyl and another carbon atom.

**Step 2: Determine which part is from the alcohol and which is from the carboxylic acid**

The ethyl tells us that there are two carbon atoms in the part of the chain from the alcohol. The prefix hex- tells us that there are six carbon atoms from the part of the chain from the carboxylic acid.

**Step 3: Place the functional group as well as any branched groups**

The oxygen atom bonded to two different carbon atoms is located between the two sections. The $-C=O$ (carbonyl) group is located at the first carbon atom of the carboxylic acid chain.

from alcohol    from carboxylic acid

**Step 4: Combine this information and add the hydrogen atoms**

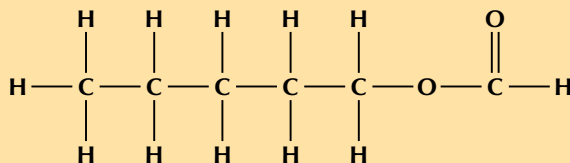
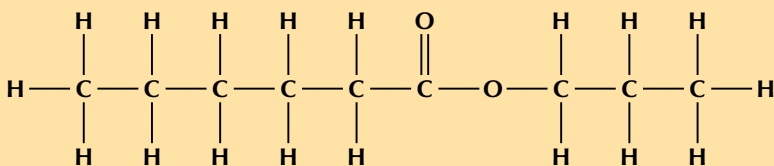
```
      H   H       O   H   H   H   H   H
      |   |       ‖   |   |   |   |   |
  H — C — C — O — C — C — C — C — C — C — H
      |   |           |   |   |   |   |
      H   H           H   H   H   H   H
```

**Step 5: Condense the structural representation**

Condense the part of the compound that came from the carboxylic acid first, so start from the right here: $CH_3CH_2CH_2CH_2CH_2COO$

The first O is for the $-C{=}O$, the second is from the $-O-$. Now condense the part that came from the alcohol, starting from the $-O-$:

$\mathbf{CH_3CH_2CH_2CH_2CH_2COOCH_2CH_3}$

**Exercise 4 – 16: Naming esters**

1. Give the IUPAC name for each of the following compounds:
   a) $CH_3COOCH_2CH_3$
   b)
   ```
         H   H   H   H   H       O
         |   |   |   |   |       ‖
     H — C — C — C — C — C — O — C — H
         |   |   |   |   |
         H   H   H   H   H
   ```
   c)
   ```
         H   H   H   H   H   O       H   H   H
         |   |   |   |   |   ‖       |   |   |
     H — C — C — C — C — C — C — O — C — C — C — H
         |   |   |   |   |           |   |   |
         H   H   H   H   H           H   H   H
   ```
2. Give the structural representations for the following esters:
   a) heptyl propanoate b) methyl octanoate c) hexyl pentanoate
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27N6 2. 27N7

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**Worked example 25: Naming carbonyl compounds**

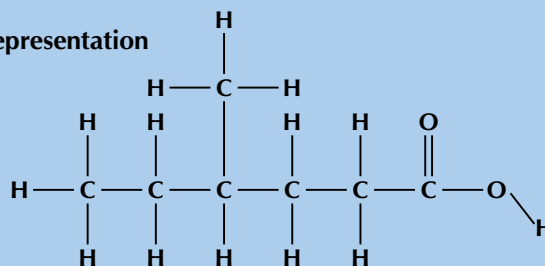
***QUESTION***

Give the IUPAC name for the following compound: $\mathbf{CH_3CH_2CH(CH_3)CH_2CH_2COOH}$

(Remember that the side groups are shown in brackets after the carbon atom to which they are attached)

***SOLUTION***

**Step 1: Draw the structural representation**

```
                       H
                       |
                   H — C — H
        H     H        |     H     H     O
        |     |        |     |     |     ||
   H — C  —  C  —      C  —  C  —  C  —  C — O
        |     |        |     |     |            \
        H     H        H     H     H             H
```

**Step 2: Identify the functional group**

The compound has a −COOH functional group. It is therefore a carboxylic acid and the suffix is -oic acid.

**Step 3: Find the longest carbon chain containing the functional group**

There are six carbon atoms in the longest chain containing the functional group. The prefix for this compound is hexan-.

**Step 4: Number the carbon atoms in the carbon chain**

The carbon atoms should be numbered from right to left so that the carboxylic acid functional group has the lowest numbered carbon atom.

**Step 5: Look for any branched groups, name them and give their position on the carbon chain**

There is a branched group attached to the fourth carbon atom. This group has only one carbon atom and is therefore a methyl group (4-methyl).

**Step 6: Combine the elements of the compound's name into a single word in the order of branched groups; prefix; name ending according to the functional group**

The compound's name is **4-methylhexanoic acid**.

**Worked example 26: Naming carbonyl compounds**

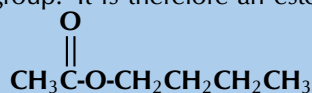
***QUESTION***

Give the IUPAC name for the following compound: $\mathbf{CH_3COOCH_2CH_2CH_2CH_3}$

***SOLUTION***

**Step 1: Identify the functional group**

The compound has a −COO functional group. It is therefore an ester and the suffix will be -oate. This can also be shown as:

$$\mathbf{CH_3\overset{\overset{\displaystyle O}{\|}}{C}\text{-}O\text{-}CH_2CH_2CH_2CH_3}$$

**Step 2: Determine which part is from the alcohol and which is from the carboxylic acid**

The left half of the compound contains the carbonyl group and is therefore from the carboxylic acid. The right half of the compound must be from the alcohol.

**Step 3: Determine the number of carbon atoms in each chain**

There are 2 carbon atoms in the part that contains the C=O group (from the carboyxlic acid), therefore the prefix is ethan-. There are 4 carbon atoms in part of the chain without the carbonyl group (from the alcohol), which is therefore butyl.

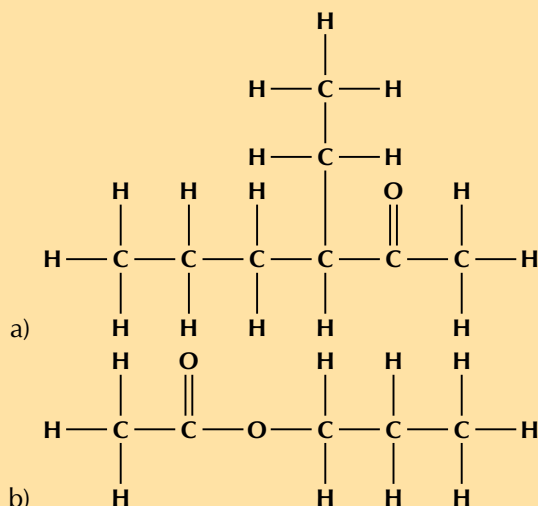
**Step 4: Look for any branched groups, name them and give their position on the carbon chain**

There are no branched groups.

**Step 5: Combine the elements of the compound's name into a single word in the order of name of chain from the alcohol; prefix (from chain containing carbonyl functional group); suffix**

The compound's name is **butyl ethanoate**.

**Exercise 4 – 17: Naming carbonyl compounds**

1. Give the structural representation for the following compounds:.
   a) 3-methylpentanal
   b) butyl pentanoate
   c) 2-methylbutanoic acid
   d) octan-4-one
2. Give the IUPAC name for each of the following compounds:

   c) $CH_3CH_2CH_2CHO$
   d) HCOOH
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27N8 2. 27N9

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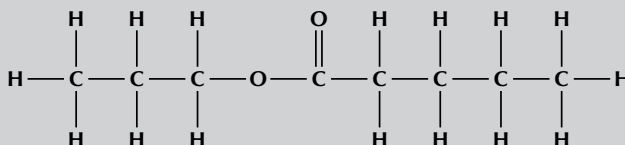
**Activity: Building molecules**

Using atomic model kits build molecules of butane, but-1-ene, but-1-yne, butan-1-ol, butanoic acid, butyl butanoate, butan-2-one, butanal. If you don't have an atomic model kit remember that you can use jelly tots (or playdough) and toothpicks. Use different colour jelly tots to represent the different atoms and extra toothpicks to represent double and triple bonds.

- Identify the functional group in each of these molecules. Move the functional group around the molecule. You should find that you can do so with but-1-ene,

but-1-yne and butan-1-ol. It will not be possible with butanoic acid and there is no functional group to move in butane.

- Can you see that if you move the carbonyl group in butan-2-one you will either still get butan-2-one or you will get butanal? Similarly, when moving the carbonyl group in butanal you can only get butanal or butan-2-one.
- Build a model of the molecule below:

```
     H   H   H       O   H   H   H   H
     |   |   |       ||  |   |   |   |
 H — C — C — C — O — C — C — C — C — C — H
     |   |   |           |   |   |   |
     H   H   H           H   H   H   H
```

Compare this to butyl butanoate. What differences are there between these two molecules? What similarities are there? What is the name of the new molecule?

- Continue by building different compounds for your friends. Make them identify the functional group, the number of carbon atoms and therefore the name of the compound.

## Exercise 4 – 18: IUPAC naming

1. Study the table below and answer the questions that follow:

| | A | B | C |
|---|---|---|---|
| | **Compound** | **Functional group** | **Number of carbon atoms** |
| **1** | *e.g. methane* | *e.g. alkane* | *e.g 1* |
| **2** | propanoic acid | alkyne | 8 |
| **3** | 2-chloroethane | ketone | 4 |
| **4** | 1-octanal | carboxylic acid | 6 |
| **5** | 3-heptyne | aldehyde | 2 |
| **6** | butanone | ester | 6 |
| **7** | 3-hexene | haloalkane | 1 and 5 |
| **8** | 1-hexanol | alkene | 3 |
| **9** | methyl pentanoate | alcohol | 7 |

   a) Match the compounds in column A with the correct functional group in column B. For example methane is an alkane: **A1**, **B1**.

   b) Match the compounds in column A with the correct number of carbon atoms in column C. For example methane has one carbon atom in its longest chain: **A1**, **C1**.

2. Match the structural representation in column A with the condensed structural representation (column B) and IUPAC name (column C).

| | A | B | C |
|---|---|---|---|
| | **Structure** | **Condensed** | **IUPAC name** |
| **1** | H H H<br>H—C—C—C—H<br>H H H | $CH_3CH(I)CH_3$ | ethyl methanoate |
| **2** | H<br>H—C—C≡C—H<br>H | $CH_3CH_2CH_3$ | propanone |
| **3** | H O H<br>H—C—C—C—H (C=O)<br>H H | $CH_3COCH_3$ | propane |

| | A | B | C |
|---|---|---|---|
| | **Structure** | **Condensed** | **IUPAC name** |
| **4** | | $HCOOCH_2CH_3$ | propyne |
| **5** | | $CH_3CCH$ | propanal |
| **6** | | $CH_3CHCH_2$ | 2-iodopropane |
| **7** | | $CH_3CH_2CHO$ | propanoic acid |
| **8** | | $CH_3CH_2COOH$ | propene |

3. Fill in the gaps in the table below:

| IUPAC name | Functional group | Condensed | Structural |
|---|---|---|---|
| | | $CH_3CH_2CH_2CHO$ | |
| ethanol | | | |
| | carboxylic acid | $CH_3CH_2CH(CH_3)CH_2COOH$ | |
| 2-methyl pent-2-ene | | $CH_3C(CH_3)CHCH_2CH_3$ | |
| | alkane | | |
| | ester | $CH_3COOCH_2CH_2CH_3$ | |
| butanone | ketone | | |
| 1-pentyne | | | |
| | alkyl halide | $CH_2(Cl)CH_2CH_3$ | |

4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27NB 2. 27NC 3. 27ND

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### Physical properties and intermolecular forces ESCKQ

The types of intermolecular forces that occur in a substance will affect its physical properties, such as its **phase**, **melting point** and **boiling point**. You should remember from the kinetic theory of matter (see Grade 10), that the *phase* of a substance is determined by how strong the forces are between its particles. The weaker the forces, the more likely the substance is to exist as a gas. This is because the particles are able to move far apart since they are not held together very strongly. If the forces are very strong, the particles are held closely together in a solid structure. Remember also that the *temperature* of a material affects the energy of its particles. The more energy the particles have, the more likely they are to be able to overcome the forces that are holding them together. This can cause a change in phase.

Figure 4.52 shows the three phases of water. Note that we are showing two-dimensional figures when in reality these are three-dimensional.

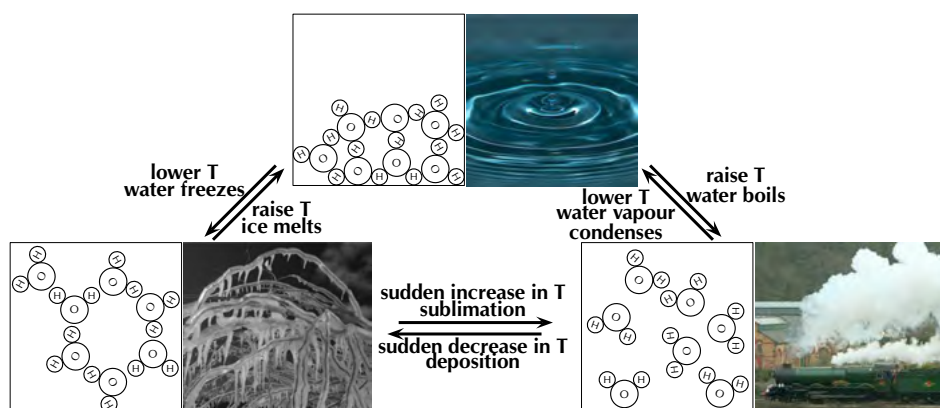



Figure 4.52: Submicroscopic diagrams of the three phases of water. (Photos by laszlo-photo, Fields of View and Capt' Gorgeous on Flickr)

#### The effects of intermolecular forces

The forces between molecules that bind them together are known as **intermolecular forces**. Intermolecular forces allow us to determine which substances are likely to dissolve in other substances, and what the melting and boiling points of substances are. Without intermolecular forces holding molecules together we would not exist.

**DEFINITION:** *Intermolecular forces*

Intermolecular forces are forces that act between molecules.

Remember from Grade 11 that a dipole molecule is a molecule that has its charge unevenly distributed. One end of the molecule is slightly positive and the other is slightly negative. An overview of the different types of intermolecular forces that are discussed in this chapter are given below:

1. **Dipole-dipole forces**
   When one dipole molecule comes into contact with another dipole molecule, the positive pole of the one molecule will be attracted to the negative pole of the other, and the molecules will be held together in this way.

One special case of this is hydrogen bonding:

- **Hydrogen bonds**

  As the name implies, this type of intermolecular bond involves a hydrogen atom. When a molecule contains a hydrogen atom covalently bonded to a small, highly electronegative atom (e.g. O, N or F) this type of intermolecular force can occur. The highly electronegative atom on one molecule attracts the hydrogen atom on a nearby molecule (see Figure 4.53).

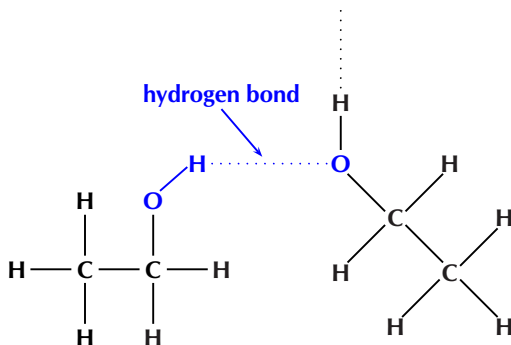



Figure 4.53: Hydrogen bonding between two molecules of ethanol.

2. **van der Waals forces**

- **Induced-dipole forces**

  In non-polar molecules the electronic charge is usually evenly distributed but it is possible that at a particular moment in time, the electrons might not be evenly distributed (remember that the electrons are always moving in their orbitals). The molecule will have a *temporary dipole*. When this happens, molecules that are next to each other attract each other very weakly.

- **Dipole-induced-dipole forces**

  These forces exist between dipoles and non-polar molecules. The dipole induces a dipole in the non-polar molecule leading to a weak, short lived force which holds the compounds together.

In this chapter we will focus on the effects of van der Waals forces and hydrogen bonding on the physical properties of organic molecules.

**TIP**

Do not confuse hydrogen bonds with *intramolecular* covalent bonds. Hydrogen bonding is an example of a scientist naming something, believing it to be one thing when in fact it was another. In this case the strength of the hydrogen bonds misled scientists into thinking this was an intramolecular bond when it is really just a strong intermolecular force.

**FACT**

Dipole-induced-dipole intermolecular forces are also sometimes called *London* forces or *dispersion* forces.

### Viscosity

Viscosity is the resistance to flow of a liquid. Think how easy it is to pour water compared to syrup or honey. The water flows much faster than the syrup or honey.

**DEFINITION:** *Viscosity*

Viscosity is a measure of how much a liquid resists flowing. i.e. The higher the viscosity, the more viscous a substance is.

Figure 4.54: Pouring water versus pouring syrup.

You can see this if you take a cylinder filled with water and a cylinder filled with glycerol (propane-1,2,3-triol). Drop a small metal ball into each cylinder and note how easy it is for the ball to fall to the bottom (Figure 4.55). In the glycerol the ball falls slowly, while in the water it falls faster.

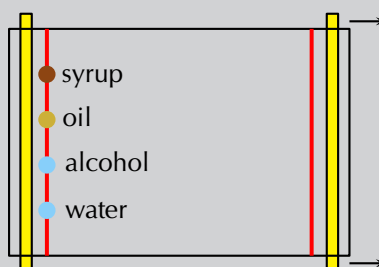
Figure 4.55: The higher the viscosity (red) the slower the ball moves through the liquid.

As implied by the definition, substances with stronger intermolecular forces are more viscous than substances with weaker intermolecular forces. The stronger the intermolecular forces the more the substance will resist flowing. The greater the internal friction the more a substance will slow down an object moving through it.

**Activity: Resistance to flow**

Take a sheet of glass at least 10 by 15 cm in size. Using a water-proof marker draw a straight line across the width of the glass about 2 cm from each end.

Place the glass flat on top of two pencils, then carefully put a drop of water on one end of the line. Leave at least 2 cm space next to the water drop, and carefully place a drop of alcohol. Repeat this with a drop of oil and a drop of syrup.

Slowly and carefully remove the pencil from the end opposite the drops (make sure you don't tilt the glass to either side in the process).

- Which drop moves fastest and reaches the end line first?
- Which drop moves slowest?

The fastest moving substance has the least resistance to flow, and therefore has the least viscosity (is the least viscous). The slowest moving substance has the most resistance to flow, and therefore has the most viscosity (is the most viscous).

### Density

**DEFINITION:** *Density*

Density is a measure of the mass per unit of volume.

The solid phase is often the most dense phase (water is one noteworthy exception to this). This can be explained by the strong intermolecular forces found in a solid. These forces pull the molecules together, which results in more molecules in one unit of volume than in the liquid or gas phases. The more molecules in a unit volume the denser, and heavier that volume of the substance will be.

Density can be used to separate different liquids, with the more dense liquid settling

to the bottom of the container, while the less dense liquid floats on top. If you throw a leaf into a river or pond the leaf will float. If you instead throw a rock (with the same surface area and volume) into the river or pond the rock will sink. This is due to the different densities of the two substances: rocks are more dense than water while leaves are less dense than water.

**FACT**
An ether is a compound that contains two alkyl chains (e.g. methyl, ethyl) joined at an angle by an oxygen atom (−O−).

**Melting and boiling points**

Intermolecular forces affect the boiling and melting points of substances. Substances with weak intermolecular forces will have low melting and boiling points as less energy (heat) is needed to overcome these forces. Those with strong intermolecular forces will have high melting and boiling points as more energy (heat) is required to overcome these forces. When the temperature of a substance is raised beyond it's melting or boiling point the intermolecular forces are not weakened. Rather, the molecules have enough energy to overcome those forces.

| Name | Main intermolecular forces | Molecular Mass ($g.mol^{-1}$) | Melting point (°C) | Boiling point (°C) | Phase (at 25°C) |
|---|---|---|---|---|---|
| ethane | induced-dipole | 30,06 | -183 | -89 | gas |
| dimethyl ether | dipole-dipole | 46,06 | -141 | -24 | gas |
| chloroethane | dipole-dipole | 64,5 | -139 | 12,3 | gas |
| pentane | induced-dipole | 72,12 | -130 | 36 | liquid |
| propan-1-ol | hydrogen bonds | 60,08 | -126 | 97 | liquid |
| ethanol | hydrogen bonds | 46,06 | -114 | 78,4 | liquid |
| butan-1-ol | hydrogen bonds | 74,1 | -90 | 118 | liquid |
| ethanoic acid | hydrogen bonds | 60,04 | 16,5 | 118,5 | liquid |

Table 4.9: Relationship between intermolecular forces and melting point, boiling point and physical state.

As the intermolecular forces increase (from top to bottom in Table 4.9) the melting and boiling points increase. The stronger the intermolecular forces the more likely a substance is to be a liquid or a solid at room temperature.

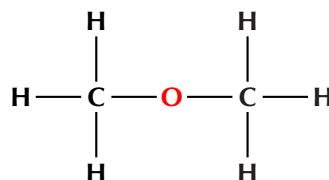



Figure 4.56: The structural formula of dimethyl ether.

**Worked example 27: Comparing physical properties**

***QUESTION***

Given:

| | Melting point (°C) | Boiling point (°C) |
|---|---|---|
| propane | −188 | −42 |
| butanoic acid | −7,9 | 163,5 |
| bromoethane | −118 | 38,5 |
| diethyl ether | −116,3 | 34,6 |

Fill in the table below:

| Name | Main intermolecular forces | Molecular formula | Molecular mass ($g.mol^{-1}$) | Phase (at 25 °C) |
|---|---|---|---|---|
| propane | | | | |
| butanoic acid | | | | |
| bromoethane | | | | |
| diethyl ether | | | | |

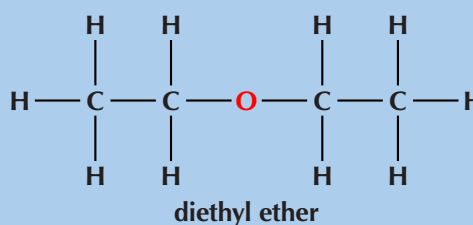
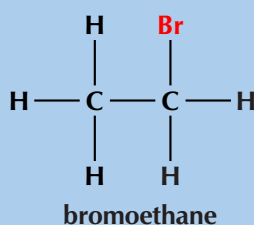
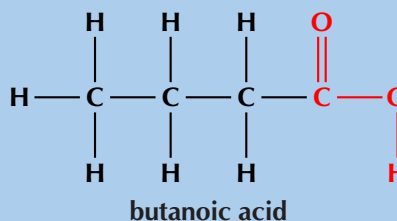
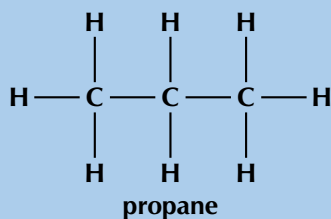
***SOLUTION***

**Step 1: Draw the structural representation of each molecule**

**propane**

**butanoic acid**

**bromoethane**

**diethyl ether**

**Step 2: What are the intermolecular forces that each molecule will experience?**

- **propane** has only single carbon-carbon bonds and no other functional group. It will therefore have induced-dipole forces only.
- **butanoic acid** has the carboxylic acid functional group. It can therefore form hydrogen bonds.
- **bromoethane** has the highly electronegative bromine atom. This means that it will form dipole-dipole interactions with neighbouring molecules.
- **diethyl ether** will have induced-dipole forces, however due to the flexible nature of the molecule is can also have dipole-induced-dipole (stronger van der Waals interactions) and dipole-dipole forces.

**Step 3: Do these forces make sense with the melting and boiling points provided?**

Propane has the lowest melting and boiling points and the weakest interactions. The next lowest melting and boiling points are for bromoethane and diethyl ether, which both have dipole-dipole interactions, the next strongest intermolecular forces. The highest melting and boiling points are for butanoic acid which has strong hydrogen bonds. Therefore these forces do make sense.

**Step 4: Calculate the molecular mass of these molecules**

- propane - $C_3H_8$, molecular mass = 44,08 $g.mol^{-1}$
- butanoic acid - $C_4H_8O_2$, molecular mass = 88,08 $g.mol^{-1}$
- bromoethane - $C_2H_5Br$, molecular mass = 108,95 $g.mol^{-1}$
- diethyl ether - $C_4H_{10}O$, molecular mass = 74,10 $g.mol^{-1}$

**Step 5: What will the phase of each compound be at 25 °C?**

To determine the phase of a molecule at 25 °C look at the melting and boiling points:

- The melting and boiling points of propane are both below 25 °C, therefore the molecule will be a gas at 25 °C.
- The melting points of butanoic acid, bromoethane and dimethyl ether are below 25 °C, however the boiling points of all three molecules are above 25 °C. Therefore these molecules will be liquids at 25 °C.

**Step 6: Fill in the table**

| Name | Main intermolecular forces | Molecular formula | Molecular mass (g.mol$^{-1}$) | Phase (at 25 °C) |
|---|---|---|---|---|
| propane | induced-dipole | $C_3H_8$ | 44,08 | gas |
| butanoic acid | hydrogen bonds | $C_4H_8O_2$ | 88,08 | liquid |
| bromoethane | dipole-dipole | $C_2H_5Br$ | 108,95 | liquid |
| diethyl ether | dipole-dipole | $C_4H_{10}O$ | 74,10 | liquid |

## Experiment: Investigation of boiling and melting points

**Aim:**

To investigate the relationship between boiling points and intermolecular forces

**Apparatus:**

- butan-1-ol ($CH_2(OH)CH_2CH_2CH_3$), propanoic acid ($CH_3CH_2COOH$) and ethyl methanoate ($HCOOCH_2CH_3$), cooking oil
- three test tubes, a beaker, a thermometer, a hot plate

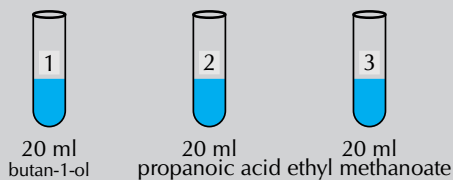
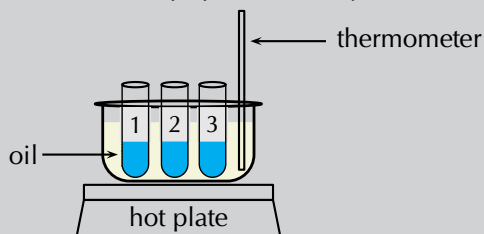
**Method:**

**WARNING!**

---

**Ethyl methanoate can irritate your eyes, skin, nose and lungs. Keep open flames away from your experiment and make sure you work in a well ventilated area.**

---

1. Label the test tubes **1**, **2** and **3**. Place 20 ml of butan-1-ol into test tube 1, 20 ml of propanoic acid into test tube 2, and 20 ml of ethyl methanoate into test tube 3.
2. Half-fill the beaker with cooking oil and place it on the hot plate.
3. Place the thermometer and the three test tubes in the beaker.
4. Make a note of the temperature when each substance starts to boil.

**Results:**

Fill in the gaps in the table below. Do the values you obtained match those reported in literature?

| Compound | ethyl methanoate | butan-1-ol | propanoic acid |
|---|---|---|---|
| **Molecular formula** | | | |
| **Molecular mass** | | | |
| **Main intermolecular forces** | | | |
| **Literature boiling point (°C)** | 54 | 118 | 141 |
| **Experimental boiling point (°C)** | | | |

Draw the structural representation of ethyl methanoate, butan-1-ol and propanoic acid.

**Discussion and conclusion:**

You should have found that the ethyl methanoate boiled first, then the butan-1-ol and then the propanoic acid. Ethyl methanoate has some dipole-dipole interactions, but cannot form a hydrogen bond. The alcohol (butan-1-ol) can form hydrogen bonds and so has a higher boiling point. This strong intermolecular force needs more energy to break and so the boiling point is higher.

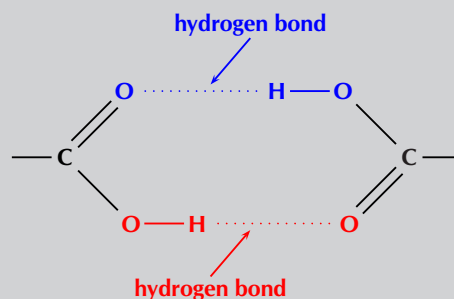



Figure 4.57: A carboxylic acid hydrogen bonding dimer.

For propanoic acid hydrogen bonds form between the carbonyl group on one acid and the hydroxyl group on another. This means that each molecule of propanoic acid can be part of two hydrogen bonds (this is called dimerisation, see Figure 4.57) and so the boiling point is even higher for propanoic acid than for butan-1-ol.

**Flammability and vapour pressure**

Flammability is a measure of how easy it would be for a substance to catch alight and burn. The *flash point* of a substance is the lowest temperature that is likely to form a gaseous mixture you could set alight. If a liquid has a low enough flash point it is considered flammable (able to be ignited easily) while those with higher flash points are considered nonflammable. A substance that is classified as nonflammable can still be forced to burn, but it will not ignite easily.

When a substance is in the liquid or solid state there will be some molecules in the gas state. These molecules have enough energy to overcome the intermolecular forces holding the majority of the substance in the liquid or solid phase. These gas molecules exert a pressure on the liquid or solid (and the container) and that pressure is the vapour pressure of that compound. The weaker the intermolecular forces within a substance the higher the vapour pressure will be. Compounds with higher vapour pressures have lower flash points and are therefore more flammable.

**DEFINITION:** *Vapour pressure*

The pressure exerted (at a specific temperature) on a solid or liquid compound by molecules of that compound that are in the gas phase.

| Name | Main intermolecular forces | Vapour pressure (kPa at 20°C) | Flash point (°C) | Flammability |
|---|---|---|---|---|
| ethane | induced-dipole | 3750 | -135 | very high |
| propane | induced-dipole | 843 | -104 | very high |
| dimethyl ether | dipole-dipole | 510 | 41 | very high |
| butane | induced-dipole | 204 | -60 | very high |
| chloroethane | dipole-dipole | 132,4 | -50 | very high |
| pentane | induced-dipole | 57,9 | -49 | very high |
| propanone | dipole-dipole | 24,6 | -17 | high |
| ethanol | hydrogen bonds | 5,8 | 17 | high |
| water | hydrogen bonds | 2,3 | - | very low |
| propan-1-ol | hydrogen bonds | 2 | 22 | high |
| ethanoic acid | hydrogen bonds | 1,6 | 40 | moderate |
| butan-1-ol | hydrogen bonds | 0,6 | 35 | high |

Table 4.10: Relationship between intermolecular forces and the flammability of a substance.

As the intermolecular forces increase (from top to bottom in Table 4.10) you can see a decrease in the vapour pressure. This corresponds with an increase in the flash point temperature and a decrease in the flammability of the substance. Figure 4.58 shows a few examples.

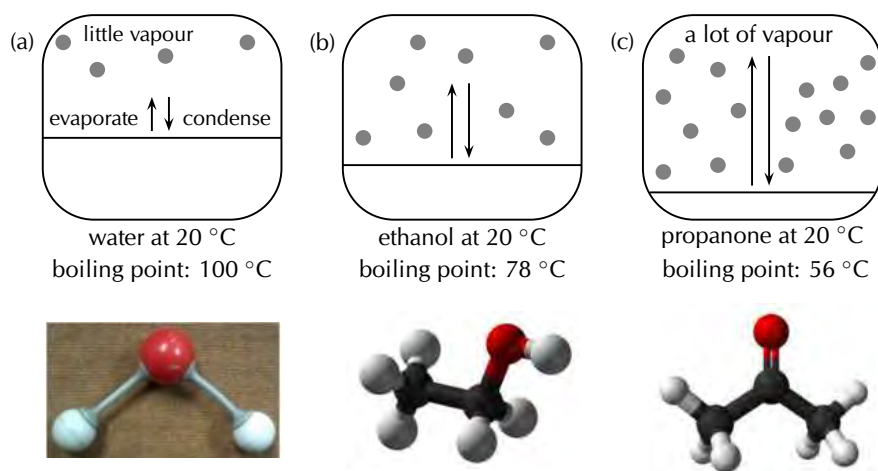



Figure 4.58: The vapour pressure of **(a)** water, **(b)** ethanol and **(c)** propanone at 20 °C. (Images by Duncan Watson)

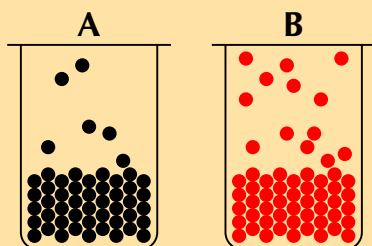
### Exercise 4 – 19: Types of intermolecular forces

1. Use your knowledge of different types of intermolecular forces to explain the following statements:
   a) The boiling point of hex-1-ene is much lower than the boiling point of propanoic acid.
   b) Water evaporates more slowly than propanone.

2.

| | IUPAC name | Boiling point (°C) |
|---|---|---|
| **A** | ethane | −89,0 |
| **B** | ethanol | 78,4 |
| **C** | ethanoic acid | 118,5 |

   a) Which of the compounds listed in the table are gases at room temperature?
   b) Name the main type of intermolecular forces for A, B and C.
   c) Account for the difference in boiling point between A and B.
   d) Account for the difference in boiling point between B and C.
   e) Draw the structural representations of A, B and C.

3. a) Which container (A or B) has the compound with higher vapour pressure in it? Explain your answer.

   b) Draw the condensed structural formula for each of these compounds:
      i. propanoic acid
      ii. butan-1-ol
   c) Propanoic acid has a vapour pressure of 0,32 kPa at 20 °C

**TIP**

Vanilla has a *sweet* smell. The smell of ethene and dimethyl ether cling in your nose though, and the smell of ether can even stay on your skin up to 24 hours.

**FACT**

In humans, ethanol reduces the secretion of a hormone called antidiuretic hormone (ADH). The role of ADH is to control the amount of water that the body retains. When this hormone is not secreted in the right quantities, it can cause dehydration because too much water is lost from the body in the urine (ethanol is a diuretic). This is why people who drink too much alcohol can become dehydrated, and experience symptoms such as headaches, dry mouth, and lethargy. Part of the reason for the headaches is that dehydration causes the brain to shrink away from the skull slightly.

Butan-1-ol has a vapour pressure of 0,64 kPa at 20 °C
Explain the difference in vapour pressure.

4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1a. 27NF 1b. 27NG 2. 27NH 3a. 27NJ 3b. 27NK 3c. 27NM

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## Physical properties and functional groups ESCKR

Compounds that contain very similar atoms can have very different properties depending on how those atoms are arranged. This is especially true when they have different functional groups. Table 4.11 shows some properties of different functional groups.

| Functional group | Typical Smell | Example | Formula | Melting point (°C) | Boiling point (°C) | Phase (at 25°C) |
|---|---|---|---|---|---|---|
| alkane | odourless | *ethane* | $C_2H_6$ | -183 | -89 | gas |
| alkene | sweet/musky | *ethene* | $C_2H_4$ | -169,2 | -103,7 | gas |
| ether (-O-) | sweet | *dimethyl ether* | $C_2H_6O$ | -141 | -24 | gas |
| haloalkane | almost odourless | *chloro ethane* | $C_2H_5Cl$ | -139 | 12,3 | gas |
| aldehyde | pungent fruity | *ethanal* | $C_2H_4O$ | -123,4 | 20,2 | gas |
| alcohol | sharp | *ethanol* | $C_2H_6O$ | -114 | 78,4 | liquid |
| ester | often fruity | *methyl methanoate* | $C_2H_4O_2$ | -100 | 32 | liquid |
| alkyne | odourless | *ethyne* | $C_2H_2$ | -80,8 | -84 | gas |
| carboxylic acid | vinegar rancid butter | *ethanoic acid* | $C_2H_4O_2$ | 16,5 | 118,5 | liquid |

Table 4.11: Some properties of compounds with different functional groups.

Listed in the table are the common smells and other physical properties found for common functional groups. Only one representative example from each homologous series is provided. This does not mean that all compounds in that series have exactly the same properties. For example, short-chain and long-chain alkanes are generally odourless, while those with moderate chain length (approximately 6 - 12 carbon atoms) smell like petrol (Table 4.15).

Some specific properties of a few functional groups will now be discussed in more detail.

**Physical properties of the alcohols**

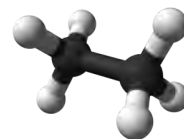
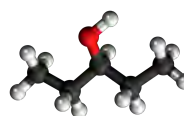
The hydroxyl group (−OH) affects the **solubility** of the alcohols.

**DEFINITION:** *Solubility*

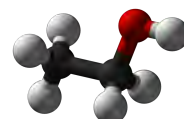
Solubility is a measure of the ability of a substance (solid, liquid or gas) to dissolve in another substance. The amount of the substance than can dissolve is the measure of its solubility.

The hydroxyl group generally makes the alcohol molecule *polar* and therefore more likely to be **soluble** in water. However, the carbon chain resists solubility, so there are two opposing trends in the alcohols. Alcohols with shorter carbon chains are usually more soluble in water than those with longer carbon chains.

Alcohols tend to have higher **boiling points** than the hydrocarbons because of the strong hydrogen bond between hydrogen atoms of one hydroxyl group and the oxygen atom of another hydroxyl group.

**FACT**
Ethane has a relatively low solubility in water.

Because hydroxyl (−OH) groups can hydrogen bond, all three pentanol molecules have a greater solubility in water than ethane.

Ethanol is completely soluble in water in any amount. This is because it contains a hydroxyl group and has a much shorter non-polar chain length than pentanol.

| pentanol | solubility (g.dm$^{-3}$) |
|---|---|
| ethane | 0,057 |
| **1**-pentanol | 22 |
| **2**-pentanol | 45 |
| **3**-pentanol | 59 |
| ethanol | soluble |

### Physical properties of haloalkanes

There can be more than one halogen substituted for a hydrogen atom on one haloalkane. The more halogens are substituted the less **volatile** the haloalkane becomes. Take for example the haloalkane series shown in Figure 4.59.

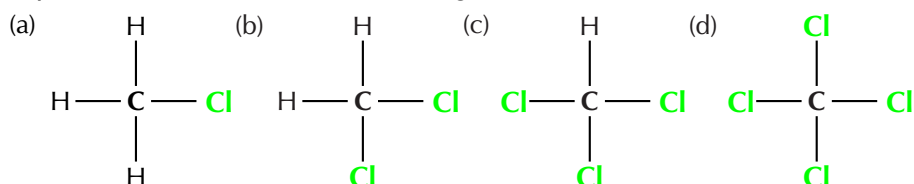



Figure 4.59: A series of haloalkanes with increasing numbers of chlorine atoms: **(a)** chloromethane, **(b)** dichloromethane, **(c)** trichloromethane and **(d)** tetracholormethane.

**DEFINITION:** *Volatility*

The tendency of molecules at the surface of a compound to enter the gas phase. The more volatile a compound the more likely this is.

For every *extra* chlorine atom on the original methane molecule the volatility of the compound decreases. This can be seen by the increase in both the melting and boiling point (Table 4.12) as one goes from chloromethane through to tetrachloromethane. The more halogen atoms in the compound the stronger the intermolecular forces are, which leads to higher melting and boiling points.

| Common Name | Number Cl atoms | Melting point (°C) | Boiling point (°C) |
|---|---|---|---|
| chloromethane | 1 | −97,4 | −24,2 |
| dichloromethane | 2 | −96,7 | 39,6 |
| trichloromethane | 3 | −63,5 | 61,2 |
| tetrachloromethane | 4 | −22,9 | 76,7 |

Table 4.12: Melting and boiling points of haloalkanes with increasing numbers of chlorine atoms.

### Properties of carbonyl compounds

Carboxylic acids are **weak acids**, in other words they only dissociate partially. Why does the carboxyl group have acidic properties? In the carboxyl group, the hydrogen tends to separate itself (dissociate) from the oxygen atom. In other words, the carboxyl group becomes a source of positively-charged hydrogen ions ($H^+$). This is shown in Figure 4.60.

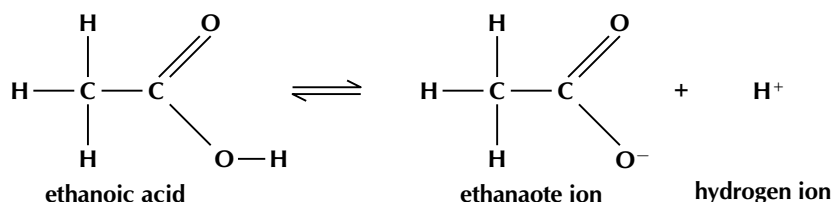



Figure 4.60: The dissociation of a carboxylic acid.

The carboxylic acid functional group is soluble in water. However, as the number of carbon atoms in the attached carbon chain increases the solubility decreases. This is discussed in greater detail in the next section.

Remember that carboxylic acids form hydrogen bonding dimers (the formation is called dimerisation) as shown in Figure 4.61.

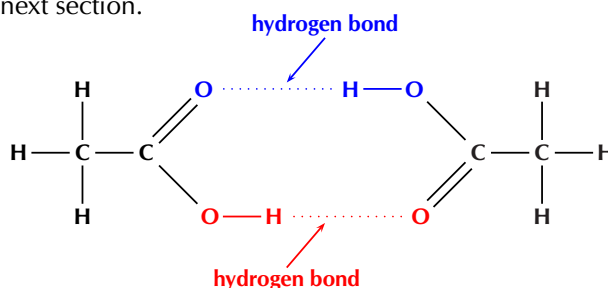



Figure 4.61: Ethanoic acid forming a carboxylic acid hydrogen bonding dimer.

The ability of a molecule to hydrogen bond leads to increased melting and boiling points when compared to a similar molecule that is unable to hydrogen bond. Similarly, the ability of a molecule to form a hydrogen bonding dimer leads to increased melting and boiling points when compared to similar molecules that can only form one hydrogen bond (Table 4.13).

| Molecule | Hydrogen bonds per molecule | Melting point (°C) | Boiling point (°C) |
|---|---|---|---|
| ethane | 0 | -183 | -89 |
| ethanol | 1 | -114 | 78,4 |
| ethanoic acid | 2 | 16,5 | 118,5 |

Table 4.13: The melting and boiling points of similar organic compounds that can form different numbers of hydrogen bonds.

### Physical properties of ketones

Hydrogen bonds are stronger than the van der Waals forces found in ketones. Therefore compounds with functional groups that can form hydrogen bonds are more likely to be soluble in water. This applies to aldehydes as well as to ketones.

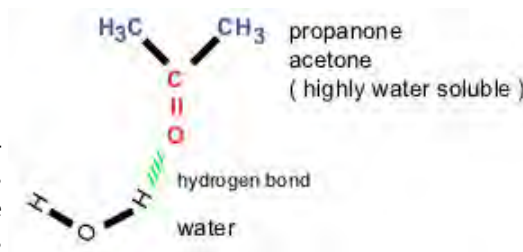



Figure 4.62: The hydrogen bond between water and a ketone (propanone).

## Exercise 4 – 20: Physical properties and functional groups

1. Refer to the data table below which shows the melting point and boiling point for a number of organic compounds with different functional groups.

| Formula | Name | Melting point (°C) | Boiling point (°C) |
|---|---|---|---|
| $C_4H_{10}$ | butane | −137 | 0 |
| $C_4H_8$ | but-1-ene | −185 | −6,5 |
| $C_4H_{10}O$ | butan-1-ol | −90 | 118 |
| $C_4H_8O_2$ | butanoic acid | −7,9 | 163,5 |
| $C_5H_{12}$ | pentane | −130 | 36 |
| $C_5H_{10}$ | pent-1-ene | −165,2 | 30 |
| $C_5H_{12}O$ | pentan-1-ol | −78 | 138 |
| $C_5H_{10}O_2$ | pentanoic acid | −34,5 | 186,5 |

a) At room temperature (approx. 25°C), which of the organic compounds in the table are:

i. gases ii. liquids

b) Look at an alkane, alkene, alcohol and carboxylic acid with the same number of carbon atoms:
   i. How do their melting and boiling points compare?
   ii. Explain why their melting points and boiling points are different?

2. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27NN

## Physical properties and chain length ESCKS

Remember that the alkanes are a group of organic compounds that contain carbon and hydrogen atoms bonded together. The carbon atoms link together to form chains of varying lengths. We have already mentioned that the alkanes are relatively unreactive because of their stable C-C and C-H bonds. The boiling points and melting points of these molecules are determined by their molecular structure and their surface area.

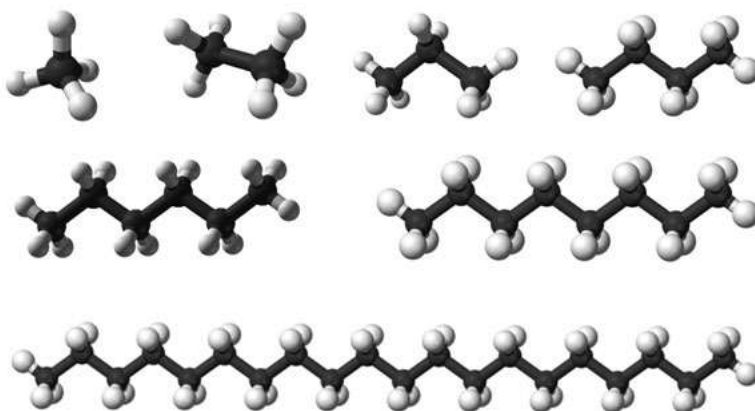



Figure 4.63: Some alkanes, from top left to bottom right: methane, ethane, propane, butane, hexane, octane and icosane.

The more carbon atoms there are in an alkane, the greater the surface area available for intermolecular interactions.

small neutral molecules

$\delta$- $\delta$+

van der Waals forces

(low boiling point)

bigger neutral molecules

(higher boiling point)

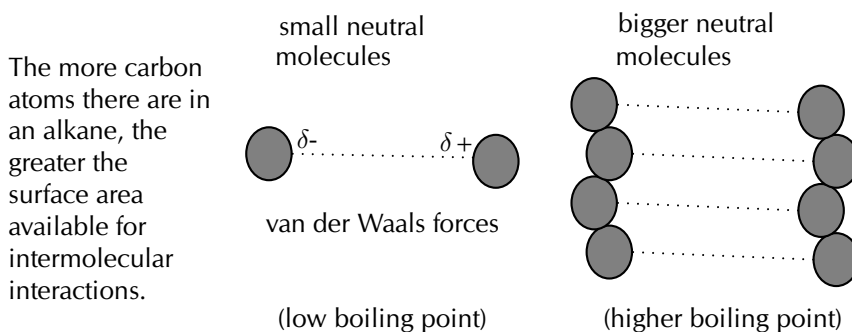



Figure 4.64: van der Waals intermolecular forces increase as chain length increases. (Image by Duncan Watson)

This increase in intermolecular attractions leads to higher melting and boiling points. This is shown in Table 4.14.

**TIP**

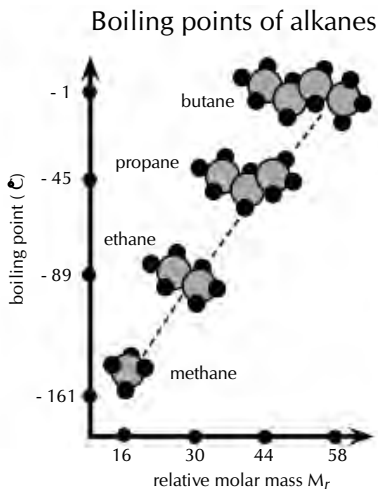
**Be careful** when comparing molecules with different types of intermolecular forces. For example, small molecule with hydrogen bonding can have stronger intermolecular forces than a large molecule with only van der Waals forces.

**FACT**

It is partly the stronger intermolecular forces that explain why petrol (mainly octane ($C_8H_{18}$)) is a liquid, while candle wax ($C_{23}H_{48}$) is a solid. If these intermolecular forces did not increase with increasing molecular size we would not be able to put liquid fuel into our cars or use solid candles.

| Formula | Name | Molecular mass (g.mol$^{-1}$) | Melting point (°C) | Boiling point (°C) | Phase (at 25°C) |
|---|---|---|---|---|---|
| $CH_4$ | methane | 16,04 | -182 | -162 | gas |
| $C_2H_6$ | ethane | 30,06 | -183 | -89 | gas |
| $C_3H_8$ | propane | 44,08 | -188 | -42 | gas |
| $C_4H_{10}$ | butane | 58,1 | -137 | 0 | gas |
| $C_6H_{14}$ | hexane | 86,14 | -95 | 68,5 | liquid |
| $C_8H_{18}$ | octane | 114,18 | -57 | 125,5 | liquid |
| $C_{20}H_{42}$ | icosane | 282,42 | 37 | 343 | solid |

Table 4.14: The physical properties of some alkanes.

Figure 4.65: As the molar mass of an alkane increases so does the boiling point. (Image by Duncan Watson)

Notice that when the molecular mass of the alkanes is low (i.e. there are few carbon atoms), the organic compounds are *gases* because the intermolecular forces are weak. As the number of carbon atoms and the molecular mass increases, the compounds are more likely to be liquids or solids because the intermolecular forces are stronger.

The larger a molecule is, the stronger the intermolecular forces are between the molecules. This is one of the reasons why methane ($CH_4$) is a gas at room temperature while hexane ($C_6H_{14}$) is a liquid and icosane ($C_{20}H_{42}$) is a solid.

Table 4.15 shows some other properties of the alkanes that also vary with chain length.

| Name | Density (g.dm$^{-3}$) | Flash point (°C) | Smell | Phase (at 25°C) |
|---|---|---|---|---|
| methane | 0,66 | -188 | odourless | gas |
| ethane | 1,28 | -135 | odourless | gas |
| propane | 2,01 | -104 | odourless | gas |
| butane | 2,48 | -60 | like petrol | gas |
| hexane | 650 | -26 | like petrol | liquid |
| octane | 700 | 13 | like petrol | liquid |
| icosane | 790 | >113 | odourless | solid |

Table 4.15: Properties of some of the alkanes.

Density increases with increasing molecular size. Note that compounds that are gaseous are much less dense than compounds that are liquid or solid.

Remember that the flash point of a volatile molecule is the lowest temperature at which that molecule can form a vapour mixture with air and be ignited. The flash point increases with increasing chain length meaning that the longer chains are less flammable (Table 4.10) although they can still be ignited.

The change in physical properties due to chain length does not only apply to the hydrocarbons. The solubility of ketones in water decreases as the chain length increases. The longer the chain length, the stronger the intermolecular interactions between the ketone molecules.

This means that more energy is required to overcome those interactions and the molecule is therefore less soluble in water. Long chains can also fold around the polar carbonyl group and stop water molecules from bonding with it.

This same idea can be applied to all the compounds with water-soluble functional groups. The longer the chain becomes, the less soluble the compound is in water.

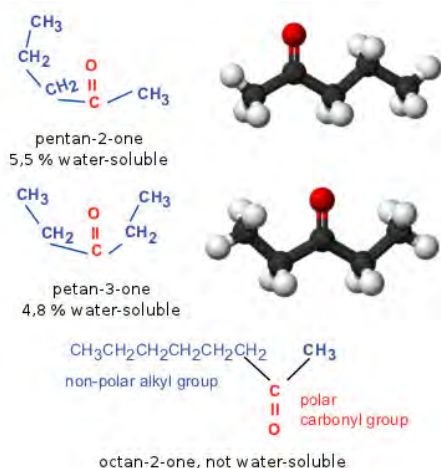



Figure 4.66: The water solubility of a ketone decreases as the chain length increases.

**Exercise 4 – 21: Physical properties and chain length**

1. Refer to the table below which gives information about a number of carboxylic acids, and then answer the questions that follow.

| Condensed formula | Common name | Source | IUPAC name | Melting point (°C) | Boiling point (°C) |
|---|---|---|---|---|---|
| | formic acid | ants | methanoic acid | 8,4 | 101 |
| $CH_3COOH$ | | vinegar | ethanoic acid | 16,5 | 118,5 |
| | propionic acid | milk | propanoic acid | -20,8 | 141 |
| $CH_3(CH_2)_2COOH$ | butyric acid | butter | | -7,9 | 163,5 |
| | valeric acid | valerian root | pentanoic acid | -34,5 | 186,5 |
| $CH_3(CH_2)_4COOH$ | caproic acid | goat skin | | -3,4 | 205,8 |
| | enanthic acid | vines | heptanoic acid | -7,5 | 223 |
| $CH_3(CH_2)_6COOH$ | caprylic acid | goat milk | | 16,7 | 239,7 |

   a) Fill in the missing spaces in the table by writing the formula, common name or IUPAC name.
   b) Draw the structural representation of butyric acid.
   c) Give the molecular formula for caprylic acid.
   d) i. Draw a graph to show the relationship between molecular mass (on the x-axis) and boiling point (on the y-axis)
      ii. Describe the trend you see. iii. Suggest a reason for this trend.

2. Refer to the data table below which shows the melting point and boiling point for a number of organic compounds with different functional groups.

| Formula | Name | Melting point (°C) | Boiling point (°C) |
|---|---|---|---|
| $C_4H_{10}$ | Butane | −137 | 0 |
| $C_5H_{12}$ | Pentane | −130 | 36 |
| $C_6H_{14}$ | Hexane | −95 | 68,5 |
| $C_4H_8$ | But-1-ene | −185 | −6,5 |
| $C_5H_{10}$ | Pent-1-ene | −165,2 | 30 |
| $C_6H_{12}$ | Hex-1-ene | −140 | 63 |

a) At room temperature (approx. 25 °C), which of the organic compounds in the table are: i. gases ii. liquids

b) In the alkanes:

i. Describe what happens to the melting point and boiling point as the number of carbon atoms in the compound increases.

ii. Explain why this is the case.

3. Fill in the table below. Under boiling point put 1 for the compound with the lowest boiling point, 2 for the next lowest boiling point until you get to 6 for the compound with the highest boiling point. Do not use specific boiling point values, but rather use your knowledge of intermolecular forces.

| Compound | Condensed Structure | Boiling point |
|---|---|---|
| propane | $CH_3CH_2CH_3$ | |
| hexane | $CH_3CH_2CH_2CH_2CH_2CH_3$ | |
| methane | $CH_4$ | e.g. 1 |
| octane | $CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_3$ | |
| butane | $CH_3CH_2CH_2CH_3$ | |
| ethane | $CH_3CH_3$ | |

4. Draw the structural representations for each of the following compounds and answer the question that follows.

a) but-2-yne b) hex-2-yne c) pent-2-yne

d) Which of these compounds will have the highest viscosity?

5. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27NP 2. 27NQ 3. 27NR 4. 27NS

## Physical properties and branched groups ESCKT

In a straight chain molecule, the carbon atoms are connected to *at most* two other carbon atoms. However, in a branched molecule some carbon atoms are connected to *three or four* other carbon atoms. This is the same principle that was discussed with primary, secondary and tertiary alcohols.

Straight chains always have higher boiling points than the equivalent molecule with branched chains. This is because the molecules with straight chains have a larger surface area that allows close contact. Branched chains have a lower boiling point due to a smaller area of contact. The molecules are more compact and cannot get too close together, resulting in fewer places for the van der Waals forces to act.

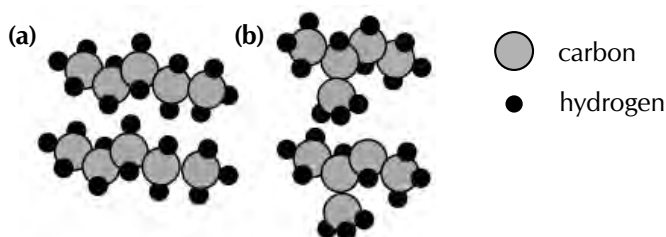



Figure 4.67: **(a)** Straight chains of pentane and **(b)** branched chains of 2-methylbutane. (Image by Duncan Watson)

Shown in Figure 4.68 are three isomers that all have the molecular formula $C_5H_{12}$. They are all alkanes with the only difference being branched groups leading to longer or shorter main chains.

(a) $CH_3 - CH_2 - CH_2 - CH_2 - CH_3$

(b) $CH_3 - CH(CH_3) - CH_2 - CH_3$

(c) $CH_3 - C(CH_3)_2 - CH_3$

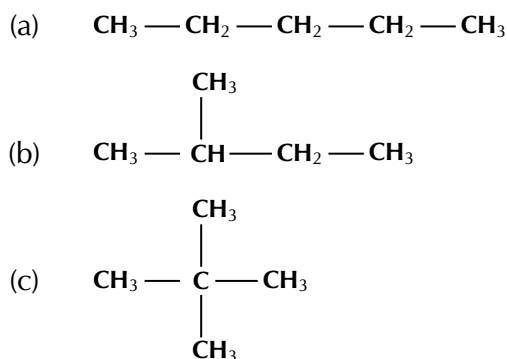



Figure 4.68: Three isomers of $C_5H_{12}$: **(a)** pentane, **(b)** 2-methylbutane and **(c)** 2,2-dimethylpropane.

As shown in Table 4.16 the properties of these three compounds are significantly different. The melting points have significant differences and the boiling points steadily decrease with an increasing number of branched groups.

| Name | Melting point (°C) | Boiling point (°C) | Density ($g.dm^{-3}$) | Vapour pressure (kPa at 20°C) | Flash point (°C) |
|---|---|---|---|---|---|
| pentane | -130 | 36 | 621 | 57,9 | -49 |
| 2-methyl butane | -160 | 27,7 | 616 | 77 | -51 |
| 2,2-dimethyl propane | -16,6 | 9,5 | 586 | 147 | <-7 |

Table 4.16: Properties of compounds with different numbers of branched groups.

Although the densities of all three compounds are very similar, there is a decrease in density with the increase of branched groups. The vapour pressure increases with increasing branched groups and the flash point of 2,2-dimethylpropane is significantly higher than those of pentane and 2-methylbutane.

It is interesting that the common trend of melting and boiling points is not followed here - 2,2-dimethylpropane has the highest melting point, lowest boiling point and is the least flammable although all three compounds are very flammable. **Symmetrical** molecules (such as 2,2-dimethylpropane) tend to have higher melting points than similar molecules with **less symmetry** due to their packing in the solid state. Once in the liquid state they follow the normal trends.

**Exercise 4 – 22: Physical properties and branched chains**

1.

| Structural Formula | Boiling point (°C) |
|---|---|
| $H-CH_2-CH_2-CH_2-CH_2-Cl$ | 78 |
| $CH_3-C(CH_3)(Cl)-CH_3$ | 51 |

a) Give the IUPAC name for each compound

b) Explain the difference in the melting points

2. There are five isomers with the molecular formula $C_6H_{14}$.
   a) Draw the structural representations of:
   2-methylpentane and 2,2-dimethylbutane (two of the isomers)
   b) What are the names of the other three isomers?
   c) Draw the semi-structural representations of these three molecules.
   d) The melting points of these three isomers are: −118, −95 and −130 °C. Assign the correct melting points to the correct isomer. Give a reason for your answers.

3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27NT  2. 27NV

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## Exercise 4 – 23: Physical properties of organic compounds

1. The table shows data collected for four organic compounds (**A** - **C**) during a practical investigation.

| | Compound | Molecular Mass ($g.mol^{-1}$) | Boiling point (°C) |
|---|---|---|---|
| **A** | $CH_3CH_2CH_3$ | 44,08 | −42 |
| **B** | $CH_3CHO$ | 44,04 | 20 |
| **C** | $CH_3CH_2OH$ | 46,06 | 78 |

   a) Is compound **A** saturated or unsaturated? Give a reason for your answer.
   b) To which homologous series does compound **B** belong?
   c) Write down the IUPAC name for each of the following compounds:
      i. **B**  ii. **C**
   d) Refer to intermolecular forces to explain the difference in boiling points between compounds **A** and **C**.
   e) Which one of compounds **B** or **C** will have the highest vapour pressure at a specific temperature? Give a reason for your answer.

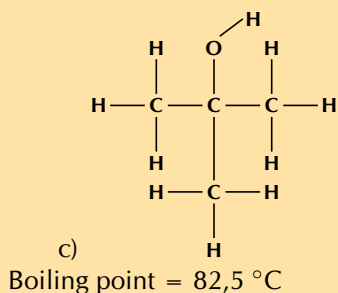
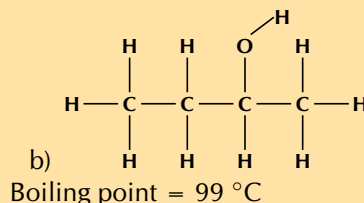
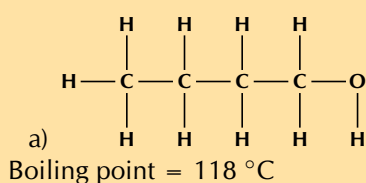
2. Give the IUPAC names for the following compounds and answer the questions that follow.

```
     H   H   H   H
     |   |   |   |
 H — C — C — C — C — O
     |   |   |   |   |
     H   H   H   H   H
```

a) Boiling point = 118 °C

```
                  H
                 /
     H   H   O   H
     |   |   |   |
 H — C — C — C — C — H
     |   |   |   |
     H   H   H   H
```

b) Boiling point = 99 °C

c) Boiling point = 82,5 °C

d) Explain the difference in boiling points.

3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27NW 2a. 27NX 2b. 27NY 2c. 27NZ 2d. 27P2

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## 4.5 Applications of organic chemistry ESCKV

### Alkanes as fossil fuels ESCKW

Fossil fuels are fuels formed by the natural process of the decomposition of organisms under heat and pressure. They contain a high percentage of carbon and include fuels such as coal, petrol, and natural gases. They are also a **non-renewable**.

**DEFINITION:** *Hydrocarbon cracking*

Hydrocarbon cracking is the process of breaking carbon-carbon bonds in long-chain hydrocarbons to form simpler, shorter-chain hydrocarbons.

**Hydrocarbon cracking** is an important industrial process. Through this process long, bulky alkanes are broken up into smaller compounds. These compounds include shorter alkanes and alkenes. A few examples of cracking hydrocarbons are given in Figure 4.69.

(a) $C_2H_6 \longrightarrow C_2H_4 + H_2$
ethane → ethene + hydrogen

(b) $C_{12}H_{26} \longrightarrow C_6H_{14} + C_2H_4 + C_4H_8$
dodecane → hexane + ethene + butene

(c) $C_{20}H_{42} \longrightarrow C_8H_{18} + C_3H_6 + C_9H_{18}$
icosane → octane + propene + nonene

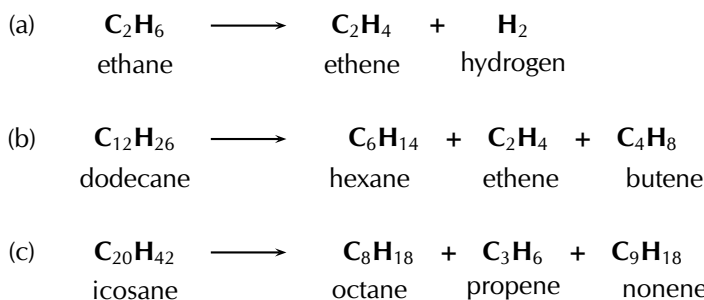



Figure 4.69: The cracking of various hydrocarbons to produce *alkanes* and *alkenes*.

There are two types of hydrocarbon cracking. **Thermal** cracking occurs under high pressures and temperatures without a catalyst, **catalytic** cracking occurs at lower pressures and temperatures in the presence of a catalyst. This process is a common source of shorter (more useful) alkanes as well as unsaturated alkenes. The alkanes are then used in combustion processes.

It is possible to separate the products of hydrocarbon cracking and obtain specific products from a crude oil mix through a process called *fractional distillation*. This is done using a *fractionating column*. Crude oil evaporates when heated to 700°C. The gas bubbles through a tray that is kept at a certain temperature. The alkanes and alkenes that condense at that temperature will then condense in the tray. For example if the tray is kept at 170°C the product will be paraffin oil (Figure 4.70).

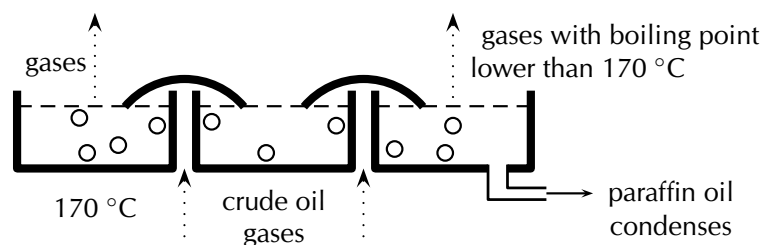



Figure 4.70: One layer of a fractionating column. (Image by Duncan Watson)

A fractionating column has a series of these trays (Figure 4.71), each at a constant temperature. This means that many compounds can be separated from the crude oil mix. The crude oil is heated to 700°C and the gas of the crude oil is passed through the column. Bitumen for tar roads is collected at the bottom of the fractionating column. These are all compounds with more than 70 carbon atoms. The temperature decreases as you move up the column. As the gases rise, compounds with different length carbon chains condense until only the chains with 1 - 4 carbon atoms are collected at the top of the column. These are used for liquid petroleum gas.

Note that this fits with what we learned in the previous section. The more carbon atoms in the chain, the greater the intermolecular forces and therefore the higher the boiling point. That means that these molecules will condense at higher temperatures.

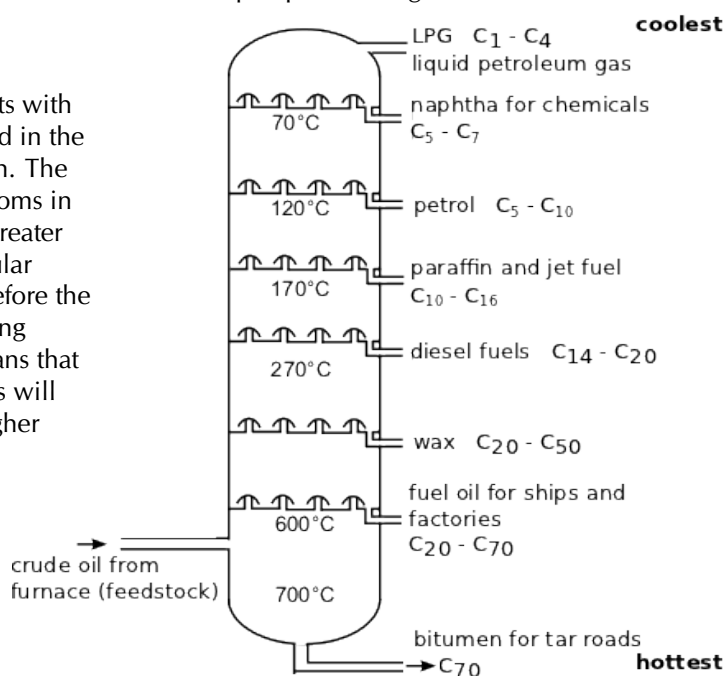



Figure 4.71: An example of a fractionating column.

For more information on the process of fractional distillation have a look at this animation:

See simulation: 27P3 at www.everythingscience.co.za

### Combustion of alkanes

Alkanes are our most important fossil fuels. The combustion (burning) of alkanes (also known as oxidation) is highly *exothermic*.

**DEFINITION:** *Combustion*

In a combustion reaction a substance reacts with an oxidising agent (e.g. oxygen), and heat and light are released.

In the complete combustion reaction of alkanes, carbon dioxide ($CO_2$) and water ($H_2O$) are released along with energy. Fossil fuels are burnt for the energy they re-

lease. The general reaction for the combustion of an alkane as a fossil fuel is given in Figure 4.72

$$\textbf{alkane} + O_2(g) \longrightarrow CO_2(g) + H_2O(g) + \textbf{energy}$$

Figure 4.72: The complete combustion of an alkane.

(a) $CH_4(g) + 2O_2(g) \longrightarrow CO_2(g) + 2H_2O(g) + \text{energy}$

(b) $C_3H_8(g) + 5O_2(g) \longrightarrow 3CO_2(g) + 4H_2O(g) + \text{energy}$

(c) $2C_6H_{14}(\ell) + 19O_2(g) \longrightarrow 12CO_2(g) + 14H_2O(g) + \text{energy}$

(d) $2C_8H_{18}(\ell) + 25O_2(g) \longrightarrow 16CO_2(g) + 18H_2O(g) + \text{energy}$

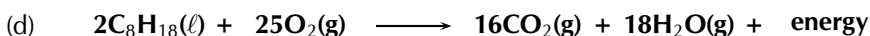
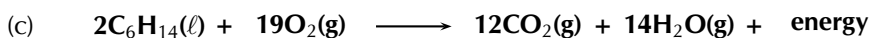
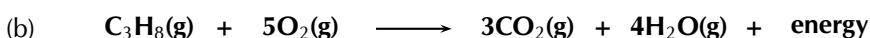
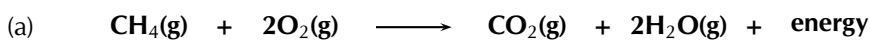



Figure 4.73: The complete combustion reactions of **(a)** methane, **(b)** propane, **(c)** hexane and **(d)** octane.

**FACT**

The complete combustion of alkanes produces only $CO_2$ and $H_2O$. Not all combustion process are complete though. An incomplete combustion will also produce carbon monoxide (CO).

**TIP**

Remember that an exothermic reaction releases energy ($\Delta H < 0$), while an endothermic reaction absorbs energy ($\Delta H > 0$). The fact that energy is released in a combustion reaction implies that $\Delta H < 0$ and the reaction is exothermic.

### Worked example 28: Balancing equations

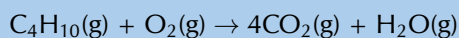
***QUESTION***

Balance the following equation: $C_4H_{10}(g) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$

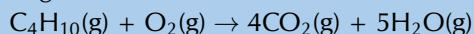
***SOLUTION***

**Step 1: Balance the carbon atoms**

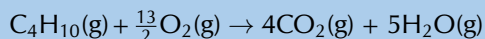
There are 4 carbon atoms on the left. There is 1 carbon atom on the right. Add a 4 in front of the $CO_2$ molecule on the right:

$$C_4H_{10}(g) + O_2(g) \rightarrow 4CO_2(g) + H_2O(g)$$

**Step 2: Balance the hydrogen atoms**

There are 10 hydrogen atoms on the left. There are 2 hydrogen atoms on the right. Add a 5 in front of the $H_2O$ molecule on the right:

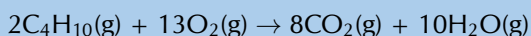
$$C_4H_{10}(g) + O_2(g) \rightarrow 4CO_2(g) + 5H_2O(g)$$

**Step 3: Balance the oxygen atoms**

There are 2 oxygen atoms on the left. There are 13 oxygen atoms on the right (4 x 2 in the $CO_2$ and 5 in the $H_2O$). Divide the number of O atoms on the right by 2 to get $\frac{13}{2}$, this is the number of $O_2$ molecules required on the left:

$$C_4H_{10}(g) + \tfrac{13}{2}O_2(g) \rightarrow 4CO_2(g) + 5H_2O(g)$$

This is acceptable but it is better for all numbers to be whole numbers.

**Step 4: Make sure all numbers are whole numbers**

There is $\frac{13}{2}$ in front of the $O_2$ while all other numbers are whole numbers. So multiply the entire equation by 2:

$$2C_4H_{10}(g) + 13O_2(g) \rightarrow 8CO_2(g) + 10H_2O(g)$$

### Worked example 29: Balancing equations

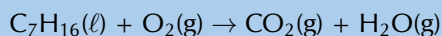
***QUESTION***

Balance the equation for the complete combustion of **heptane**

***SOLUTION***

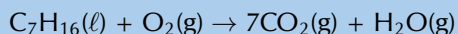
**Step 1: Write the unbalanced equation**

The molecular formula for heptane is $C_7H_{16}$. Combustion always involves oxygen ($O_2$). The complete combustion of an alkane always produces carbon dioxide ($CO_2$) and water ($H_2O$):

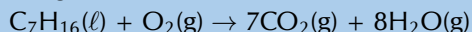
$$C_7H_{16}(\ell) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$$

**FACT**
In the formation of an ester one oxygen atom comes from the alcohol molecule, while the carbonyl group comes from the carboxylic acid. This is known because it is possible to *label* (using radioactive nuclides) the atoms of the reactants and see where they end up in the products.

**Step 2: Balance the carbon atoms**

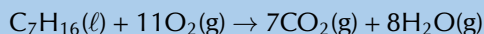
There are 7 carbon atoms on the left. There is 1 carbon atom on the right. Add a 7 in front of the $CO_2$ molecule on the right:

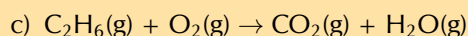
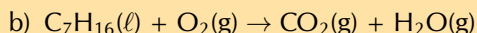
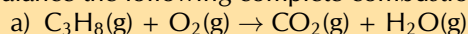
$$C_7H_{16}(\ell) + O_2(g) \rightarrow 7CO_2(g) + H_2O(g)$$

**Step 3: Balance the hydrogen atoms**

There are 16 hydrogen atoms on the left. There are 2 hydrogen atoms on the right. Add an 8 in front of the $H_2O$ molecule on the right:

$$C_7H_{16}(\ell) + O_2(g) \rightarrow 7CO_2(g) + 8H_2O(g)$$

**Step 4: Balance the oxygen atoms**

There are 2 oxygen atoms on the left. There are 22 oxygen atoms on the right (7 x 2 in the $CO_2$ and 8 in the $H_2O$). Divide the number of O atoms on the right by 2 to get 11, this is the number of $O_2$ molecules required on the left:

$$C_7H_{16}(\ell) + 11O_2(g) \rightarrow 7CO_2(g) + 8H_2O(g)$$

**Exercise 4 – 24: Alkanes as fossil fuels**

1. Balance the following complete combustion equations:
   a) $C_3H_8(g) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$
   b) $C_7H_{16}(\ell) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$
   c) $C_2H_6(g) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$
2. Write the balanced equation for the complete combustion of:
   a) octane b) pentane c) hexane d) butane
3. Is the combustion of alkanes exothermic or endothermic? What does that mean?
4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1a. 27P4 1b. 27P5 1c. 27P6 2a. 27P7 2b. 27P8 2c. 27P9
2d. 27PB 3. 27PC

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## Esters ESCKX

**Production of esters**

As was discussed earlier in this chapter one way to form an ester is through the reaction of an alcohol and a carboxylic acid. This process is called an **acid-catalysed condensation** or **esterification** of a carboxylic acid.

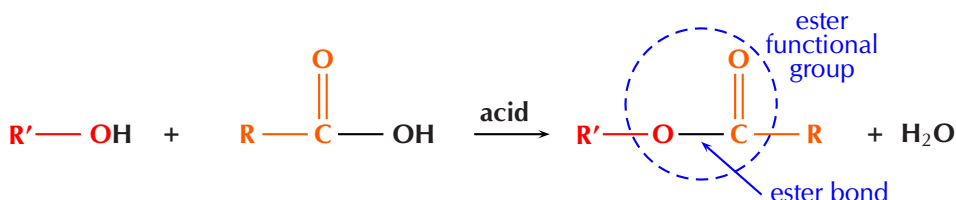



Figure 4.74: The acid-catalysed condensation of a carboxylic acid to form an ester.

In the general form above an alcohol (red) and a carboxylic acid (orange) combine to form an ester and water. A specific example is given in Figure 4.75 for the formation of butyl propanoate and water.

$$CH_3(CH_2)_3-OH + CH_3CH_2-\overset{\overset{O}{\|}}{C}-OH \longrightarrow CH_3(CH_2)_3-O-\overset{\overset{O}{\|}}{C}-CH_2CH_3 + H_2O$$

ester bond

butanol propanoic acid butyl propanoate

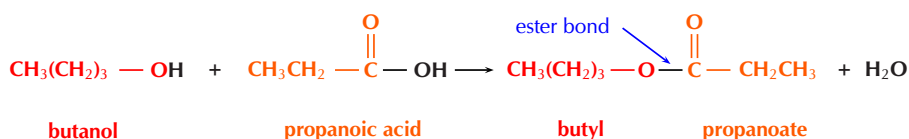
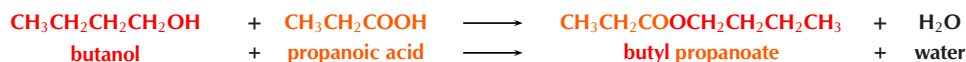



Figure 4.75: The esterification of butanol and propanoic acid to form butyl propanoate, water is also formed in this reaction.

This reaction can also be written as:

| $CH_3CH_2CH_2CH_2OH$ | + | $CH_3CH_2COOH$ | $\longrightarrow$ | $CH_3CH_2COOCH_2CH_2CH_2CH_3$ | + | $H_2O$ |
|---|---|---|---|---|---|---|
| butanol | + | propanoic acid | $\longrightarrow$ | butyl propanoate | + | water |

A more general example is:

**alcohol + carboxylic acid ⟶ ester + water**

It is important to be able to identify what ester a specific alcohol and carboxylic acid will form. Remember that the first part of the ester name takes its prefix from the alcohol with the suffix -yl. The second part of the ester takes its prefix from the carboxylic acid with the ester suffix -oate.

**Worked example 30: Determining ester names**

***QUESTION***

What is the name of the ester that will form from **hexanol** and **propanoic acid**

***SOLUTION***

**Step 1: Which compound forms the first part of the ester name and which forms the second part of the ester name?**

The alcohol forms the first part of the ester name and takes the suffix *-yl*. The carboxylic acid forms the second part of the ester name and takes the suffix *-oate*.

**Step 2: Determine the first part of the ester name**

The alcohol is *hex*anol, therefore there are 6 carbons and this will be hexyl.

**Step 3: Determine the second part of the ester name**

The carboxylic acid is *propan*oic acid, therefore there are 3 carbons and this will be propanoate.

**Step 4: Combine the first and second parts of the ester name**

The ester will be **hexyl propanoate**.

It is also important to be able to determine which compounds were used to form an ester.

**Worked example 31: Determining starting materials of esters**

***QUESTION***

What compounds did the ester **octyl heptanoate** come from?

***SOLUTION***

**Step 1: What types of compounds are used to form esters?**

Esters are formed from alcohols (which become the first part of the ester name) and carboxylic acids (which become the second part of the ester name).

**Step 2: Determine the prefix for the alcohol**

The first part of the ester name comes from the alcohol (-ol). Therefore the prefix is *oct-*.

**Step 3: Determine the prefix for the carboxylic acid**

The second part of the ester name comes from the carboxylic acid (-oic acid). Therefore the prefix is *hept-*.

**Step 4: Determine the compounds use to form the ester**

Octyl heptanoate was formed from **octanol** and **heptanoic acid**.

A few examples of esters are given in Table 4.17.

| Ester name | Smell | Uses | | |
|---|---|---|---|---|
| methyl methanoate | ether | quick-dry finishes | insecticide | pharmaceuticals |
| ethyl methanoate | rum | lacquers | safety glass | fumigating foods |
| propyl methanoate | pears | solvent | flavour | fragrance |
| methyl ethanoate | glue | glues | paints | nail polish remover |
| ethyl ethanoate | apple | glues etc | solvents | decaffeination |
| propyl ethanoate | pear | solvent | flavour | fragrance |
| butyl ethanoate | banana or apple | lacquers | flavour | |
| pentyl ethanoate | banana or apple | lacquers | solvents | resins |
| methyl butanoate | apple or pineapple | flavour | fragrance | |
| ethyl butanoate | pineapple | flavour | fragrance | plasticiser |
| propyl hexanoate | blackberry or cheese | flavour | solvent | fragrance |

Table 4.17: The uses of some esters.

The following experiment will help you to prepare esters. Use what you have learned in this section to answer the questions that follow.

**Experiment: Preparation of esters**

**Aim:**

To prepare and identify esters.

**Apparatus:**

- Methanol ($CH_3OH$), ethanol ($CH_3CH_2(OH)$), pentan-1-ol ($CH_3CH_2CH_2CH_2CH_2(OH)$), methanoic acid ($HCOOH$), ethanoic acid ($CH_3COOH$), sulfuric acid ($H_2SO_4$)
- Marble chips (or small, clean stones)

- Five tall test tubes or beakers, a water bath, a hot-plate (or bunsen burner), a thermometer, rubber bands, paper towel, five bowls of cold water

**Method:**

**WARNING!**

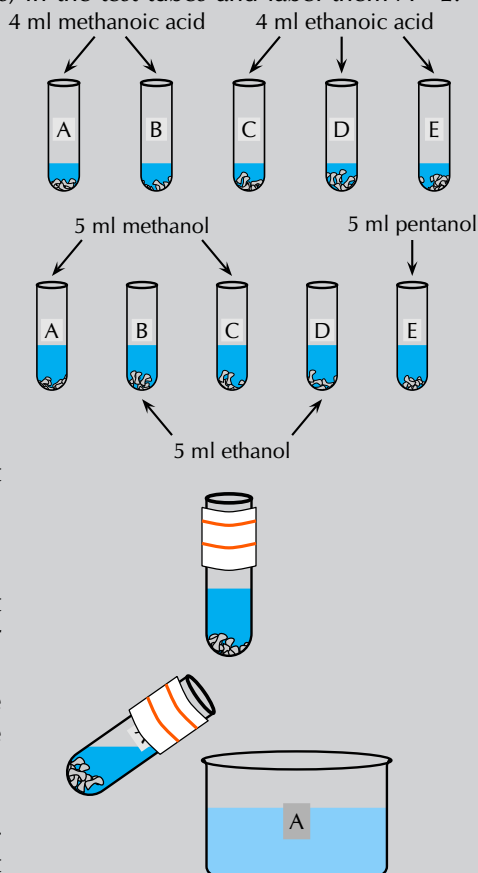
---

**Concentrated acids can cause serious burns. We suggest using gloves and safety glasses whenever you work with an acid. Always add the acid to the water and avoid sniffing the acid.**

**Remember that all alcohols are toxic, methanol is particularly toxic and can cause blindness, coma or death. Handle all chemicals with care.**

---

1. Place the marble chips (or clean stones) in the test tubes and label them *A* - *E*.
2. Add 4 ml methanoic acid to test tubes **A** and **B**.
3. Add 4 ml ethanoic acid to test tubes **C**, **D** and **E**.

4. Add 5 ml methanol to test tubes **A** and **C**.
5. Add 5 ml ethanol to test tubes **B** and **D**.
6. Add 5 ml pentanol to test tube **E**.
7. **Slowly** add 2 ml $H_2SO_4$ to each test tube.
8. Soak the paper towel in cold water and attach it to the sides near the top of each test tube with a rubber band (do not close the test tube, just wrap the paper around the sides near the top).
9. Heat the water bath to 60 °C (using the hot-plate or bunsen burner) and place the test tubes in it for 10-15 min.
10. After 10-15 min cool each test tube in cold water. Label the bowls of cold water *A* - *E* and pour the contents of test tube A into bowl A, etc.
11. Observe the surface of the water and note the smell in each bowl.

**Questions:**

1. What is the purpose of the $H_2SO_4$?
2. What is the purpose of the wet paper towel?
3. What did you observe on the top of the water in each bowl at the end?
4. Fill in the details in a table like this one:

| Carboxylic acid | Alcohol | Product | Smell |
|---|---|---|---|
| methanoic acid | methanol | | |
| methanoic acid | ethanol | | |
| ethanoic acid | methanol | | |
| ethanoic acid | ethanol | | |
| ethanoic acid | pentanol | | |

**Discussion and Conclusion:**

An ester is the product of an acid-catalysed condensation between an alcohol and a carboxylic acid. Esters have identifiable aromas (like the fragrant smell and odour of fruit) and are used in perfumes. If you didn't smell anything it is likely that your water bath was set at too high a temperature and the ester degraded.

Esters are less water soluble than the carboxylic acid they were formed from and appear as an oily substance on water. Before being cooled however some of the ester would have been a vapour, so the wet paper towel would help to prevent a loss of the product.

Refer to Table 4.17 and see if the smells match those listed there. Remember to waft the smell towards you using your hand, do not sniff the fumes directly!

**Exercise 4 – 25: Esters**

1. Give the IUPAC name for the product in the esterification of ethanoic acid with:
   a) methanol b) octanol c) hexanol d) propanol
2. What is another name for the type of reaction in the question above?
3. Give the IUPAC name for the product in the reaction of butanol with:
   a) ethanoic acid b) pentanoic acid c) heptanoic acid d) methanoic acid
4. Fill in the missing reactant or part of the product name in the reactions below:
   a) octanol + ______ $\rightarrow$ ______ hexanoate
   b) ______ + propanoic acid $\rightarrow$ hexyl ______
   c) ______ + butanol $\rightarrow$ ______ pentanoate
5. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1a. 27PD 1b. 27PF 1c. 27PG 1d. 27PH 2. 27PJ 3a. 27PK
3b. 27PM 3c. 27PN 3d. 27PP 4a. 27PQ 4b. 27PR 4c. 27PS

## 4.6 Addition, elimination and substitution reactions ESCKY

We will study three main types of reactions - addition, elimination and substitution.

- An **addition reaction** occurs when two or more reactants combine to form a single product. This product will contain *all* the atoms that were present in the reactants. Addition reactions occur with **unsaturated** compounds.

  The general equation for an **addition** reaction: A + B $\rightarrow$ C

  Notice that C is the final product with no A or B remaining as a residue.
- An **elimination reaction** occurs when a reactant is broken up into two products. Elimination reactions occur with **saturated** compounds.

  The general equation for an **elimination** reaction: A $\rightarrow$ B + C
- A **substitution reaction** occurs when an exchange of elements in the reactants takes place. The initial reactants are transformed or *swopped around* to give a final product.

  The general equation for a **substitution** reaction: AB + CD $\rightarrow$ AD + BC

Some specific examples of these reactions are given in the following pages.

## Addition reactions ESCKZ

1. **Hydrohalogenation**

   Hydrohalogenation involves the addition of a **hydrogen atom** and a **halogen atom** to an unsaturated compound (containing a carbon-carbon double bond). An example is given in Figure 4.76. X can be fluorine (F), chlorine (Cl), bromine (Br) or iodine (I).

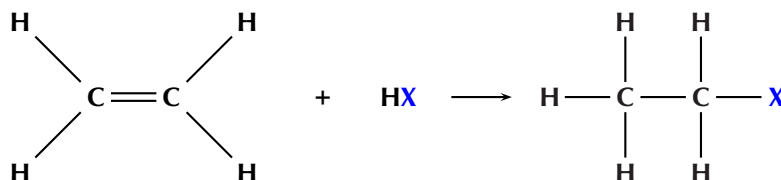



Figure 4.76: The hydrohalogenation of *ethene* to a *haloethane*.

   If more than one product is possible the **major product** will be the compound where:

   - the **hydrogen atom** is added to **least substituted carbon atom**
   - i.e. the carbon atom with the least number of carbon atoms bonded to it
   - the **halogen atom** is added to the **more substituted carbon atom**
   - i.e. the carbon atom with the most number of carbon atoms bonded to it

   This is shown in Figure 4.77.

**DEFINITION:** *Major and minor products*

The major product of a reaction is the product that is most likely to form.
Minor products are those that are less likely to form.

Figure 4.77: The hydrohalogenation of *2-methylpropene* to form **2-fluoro-2-methylpropane** (major product) and **1-fluoro-2-methylpropane** (minor product).

   Reaction conditions:
   - **no water** present in the reaction

2. **Halogenation**

   Halogenation is very similar to hydrohalogenation but a **diatomic halogen molecule** is added across the double bond. An example is given in Figure 4.78.

**FACT**

Remember from the section on saturated and unsaturated structures that you can perform tests to determine if a compound is saturated or not. If bromine water or potassium permanganate are decolourised by a compound the compound is unsaturated, if they are not decolourised the compound is saturated.

**TIP**

Remember that a **tertiary carbon atom** is bonded to three other carbon atoms, a **secondary carbon atom** is bonded to two other carbon atoms, and a **primary carbon atom** is bonded to one other carbon atom. So tertiary is the most substituted, secondary is less substituted than tertiary and more substituted than primary, and primary is the least substituted.

**FACT**

*Fermentation* can refer to the conversion of sugar to alcohol using yeast (a fungus). The process of fermentation produces items such as wine, beer and yogurt. To make wine, grape juice is fermented to produce alcohol. This reaction is shown below:
$C_6H_{12}O_6 \rightarrow 2CO_2 + 2C_2H_5OH +$ energy

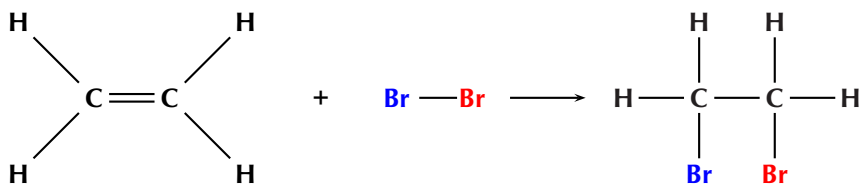
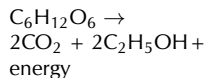



Figure 4.78: The reaction between *ethene* and *bromine* to form *1,2-dibromoethane*.

3. **Hydration**

A hydration reaction involves the addition of **water** ($H_2O$) to an **unsaturated compound**. This is one way of preparing an alcohol from the corresponding alkene (Figure 4.79).

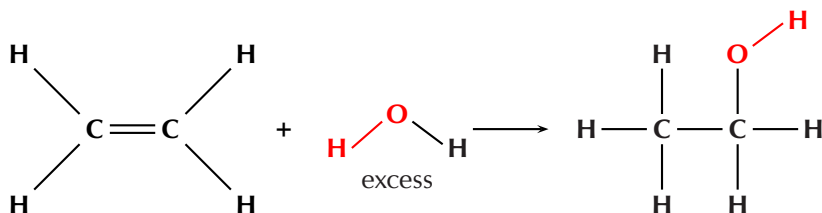
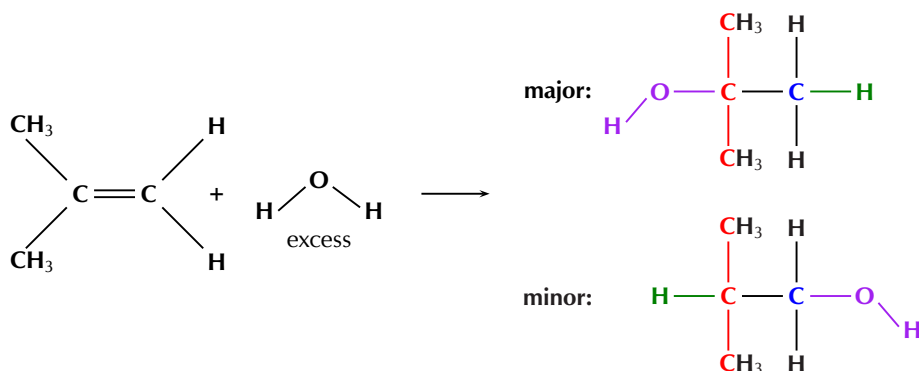



Figure 4.79: The hydration of *ethene* to *ethanol*.

If more than one product is possible the **major product** will be the compound where:

- the **hydrogen atom** is added to the **least substituted carbon atom**
- the **hydroxyl anion** ($OH^-$) is added to the **more substituted carbon atom**

major:

minor:

excess

Figure 4.80: The hydration of *2-methylpropene* to form **2-methylpropan-2-one** (major product) and **2-methyl-propan-1-one** (minor product).

Reaction conditions:

- water must be present in **excess**
- an **acid catalyst** is needed for this reaction to take place
- the catalyst that is most commonly used is phosphoric acid ($H_3PO_4$)

**Activity: Formation of alcohol through fermentation**

Ethanol can also be formed through the process of fermentation. In almost every country there is a local product that people make by fermenting local fruits. For example in Malawi people ferment potatoes, sugar cane or maize to form *katchasu*. Here in South Africa people ferment marula fruit to make *mampoer*, grapes to make *witblits* and sorghum to make beer.

- Research the chemistry behind the fermentation process.

- What other plants do people ferment?
- Fermentation leads to acid formation, research why this occurs.
- Sorghum is also used to make sour porridge. How is it made?

4. **Hydrogenation**

Hydrogenation involves adding **hydrogen** ($H_2$) to an **alkene**. During hydrogenation the double bond is broken (as with hydrohalogenation and halogenation) and more hydrogen atoms are added to the molecule. A specific example is shown in Figure 4.82.

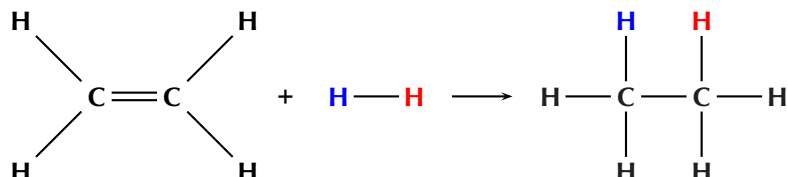



Figure 4.81: The hydrogenation of *ethene* to *ethane*.

Reaction conditions:

- a **catalyst** such as platinum (Pt), palladium (Pd) or nickel (Ni) is needed for these reactions
- **heating** is required
- the reaction must be done under an **inert atmosphere**, not air (e.g. $N_2$(g) atmosphere)

The hydrogenation of vegetable oils to form margarine is another example of this addition reaction (see Figure 4.82).

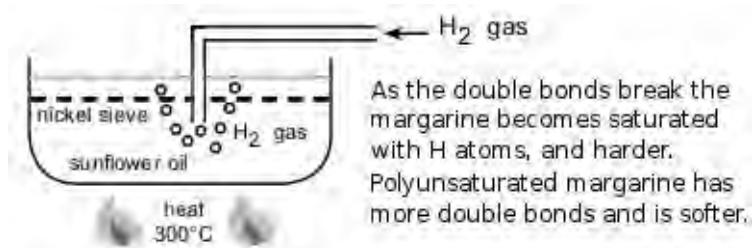



Figure 4.82: The hydrogenation of sunflower oil to make margarine.

5. **Polymerisation reactions**

A polymer is made up of lots of smaller units called *monomers*. When these monomers are added together, they form a polymer. One way for *polymerisation* to occur is through an **addition** reaction. More details are given later in this chapter in *Plastics and polymers* (Section 4.7).

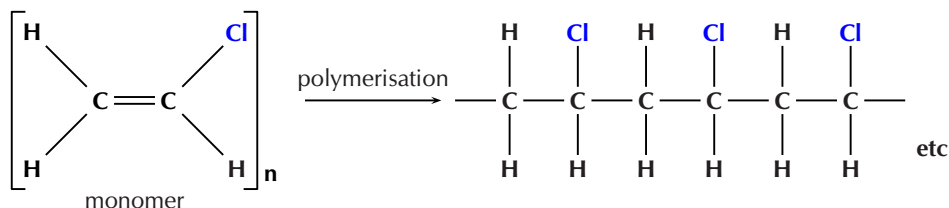
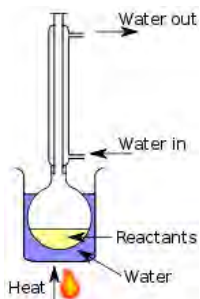
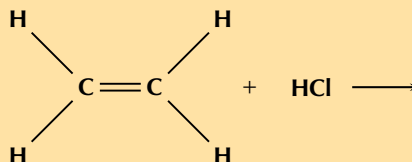



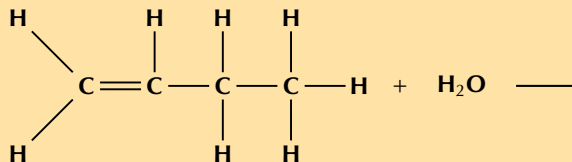
Figure 4.83: The polymerisation of **vinyl chloride** monomers to form a **polyvinyl chloride** polymer.

Polyvinyl chloride (Figure 4.101) is used in construction and in clothing, as well as having many other uses.

**FACT**
Reflux is a technique whereby a reaction solution is placed in a container with a small opening at the top. A tube that is constantly being cooled is connected to the opening. The solution is heated to approximately its boiling point, but any gases produced are condensed in the tube and fall back into the container. This way the reaction rate can be increased without the loss of material.

**TIP**
See hydrolysis in the substitution reactions section for more information on what happens when different reaction conditions are used.

## Exercise 4 – 26: Addition reactions

1. The following diagram shows the reactants in an addition reaction.

   a) Draw the structural representation of the final product in this reaction.
   b) What is the condensed structural representation of the product?

2. The following diagram shows the reactants in an addition reaction.

   a) Draw the structural representation of the major product in this reaction and give reasons.
   b) Draw the structural representation of the minor product in this reaction and give reasons.
   c) What type of addition reaction is this reaction?

3. a) Which types of homologous series can undergo addition reactions?
   b) Is this a saturated or unstaturated series?

4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27PT 2. 27PV 3. 27PW

## Elimination reactions ESCM2

1. **Dehydrohalogenation**
   In dehydrohalogenation a **haloalkane** is exposed to a **base**, the base then helps the elimination of the halogen and a hydrogen atom. A double bond is formed (alkane → alkene). Dehydrohalogenation is considered the opposite of hydrohalogenation. The elimination of iodine from iodoethane is an example of dehydrohalogenation (Figure 4.84).

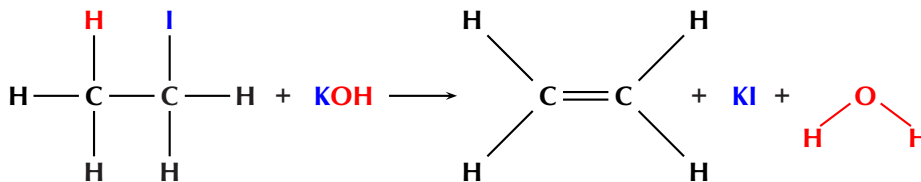



Figure 4.84: The dehydrohalogenation of *iodoethane* with potassium hydroxide (KOH) to form *ethene*, potassium iodide (KI) and water.

In order for elimination to occur the following reaction conditions must be used:

- heat under reflux (approximately 70°C)
- a concentrated, strong base (e.g. NaOH, KOH)
- the base must be dissolved in pure ethanol (hot ethanolic base)

Dihalogenated saturated compounds can also undergo elimination reactions to become unsaturated, losing one halogen and one hydrogen atom. In the example below (Figure 4.85), an atom of hydrogen and chlorine are **eliminated** from the original compound to form an unsaturated haloalkene and hydrochloric acid.

**FACT**
Sulfuric acid ($H_2SO_4$) is a dehydrating agent and is often used to prepare dried fruits.

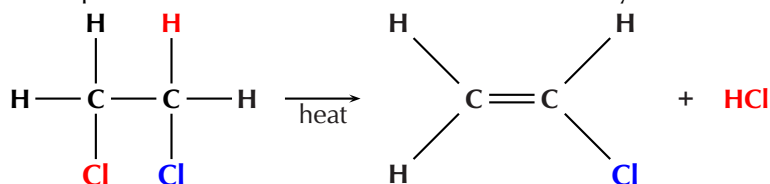



Figure 4.85: The elimination of hydrochloric acid (HCl) from *1,2-dichloroethane* to form *chloroethene*.

If more than one product is possible the major product will be the compound where:

- the hydrogen atom is removed from the **more substituted carbon atom**
- i.e. the carbon that is bonded to the most number of carbon atoms

See Figure 4.86.

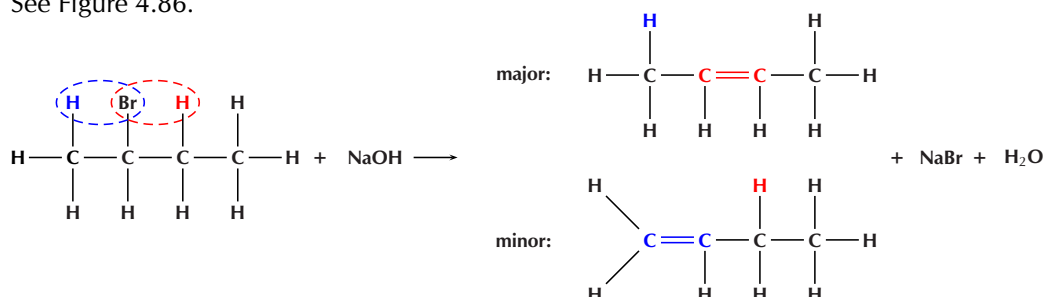



Figure 4.86: The dehydrohalogenation of *2-bromobutane* to form **but-2-ene** (major product) and **but-1-ene** (minor product).

2. **Dehydration of an alcohol**
   During the dehydration of an alcohol the **hydroxyl** (−OH) group and a **hydrogen atom** are **eliminated** from the reactant. A molecule of water is formed as a product in the reaction, along with an alkene (Figure 4.87). This can be thought of as the reverse of a hydration (addition) reaction.

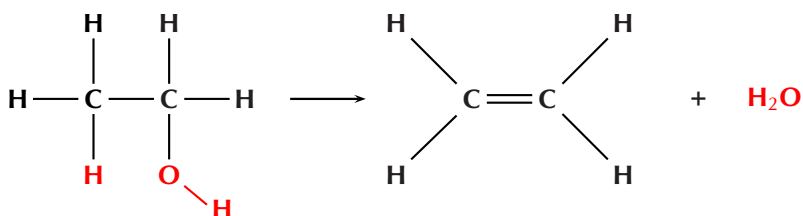



Figure 4.87: The dehydration of *ethanol* to form *ethene* and $H_2O$.

Reaction conditions:

- an **excess** of a **strong acid catalyst** (generally $H_2SO_4$ or $H_3PO_4$)
- high temperature (approximately 180°C)

If more than one elimination product is possible the major product will be the compound where:

- the hydrogen atom is removed from the carbon atom bonded to the most number of carbon atoms (i.e., the **more substituted carbon atom**)

This is shown in Figure 4.88.

Figure 4.88: The dehydration of *butan-2-ol* to form **but-2-ene** (major product) and **but-1-ene** (minor product).

**Exercise 4 – 27: Elimination reactions**

1. Answer the following questions about elimination reactions:
   a) What two compounds do you need for a dehydrohalogenation reaction?
   b) What carbon atom will the hydrogen atom be removed from in a dehydration reaction (major product)?
2. a) Are the reactants in an elimination reaction saturated or unsaturated?
   b) Name the elimination reaction that is considered the reverse of a hydration addition reaction
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27PX 2. 27PY

## Substitution reactions ESCM3

Some simple examples of substitution reactions are shown below:
$CH_4 + Cl_2 \rightarrow CH_3Cl + HCl$

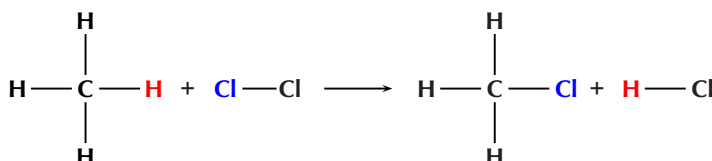
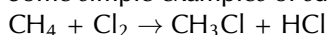



Figure 4.89: A chlorine atom (from $Cl_2$) and a hydrogen atom (from $CH_4$) are exchanged to create new products ($CH_3Cl$ and HCl).

1. **Formation of haloalkanes**

   Haloalkanes can be formed when the hydroxyl (–OH) group of an **alcohol** is replaced by a **halogen atom** (X = Cl, Br). This reaction works best with tertiary alcohols where it can occur at room temperature (Figure 4.90)

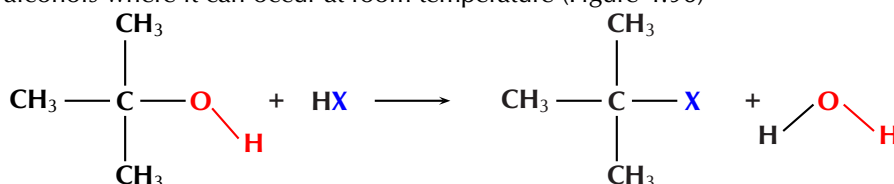



Figure 4.90: The formation of a *tertiary haloalkane* from a *tertiary alcohol* by a substitution with HX (X = Cl, Br).

A *tertiary* carbon atom is attached to three other carbon atoms. A *secondary* carbon atom is attached to two other carbon atoms while a *primary* carbon atom is attached to one other carbon atom. In Figure 4.90 the carbon is attached to the functional group as well as three other carbon atoms. This makes it a tertiary alcohol on the left of the arrow and a tertiary haloalkane on the right.

It is possible for a secondary or primary alcohol to form a secondary or primary haloalkane as well (see Figure 4.91) but this requires high temperatures and the reaction is very slow.

**TIP**
See dehydrohalogenation in the elimination reactions section for more information on what happens when different reaction conditions are used.

$$CH_3CH_2OH + HX \xrightarrow{\text{heat}} CH_3CH_2X + H_2O$$

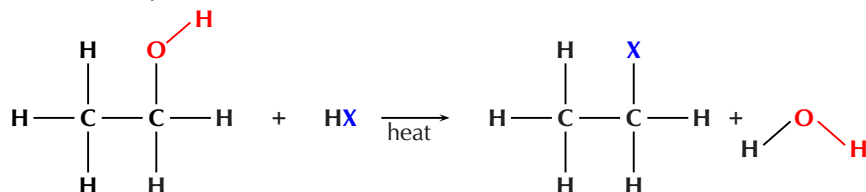



Figure 4.91: The formation of a *primary haloethane* from *ethanol* by a substitution with HX (X = Cl, Br).

2. **Hydrolysis**

   In a previous section we saw the hydration of an ethene to form an alcohol. That is an addition reaction. Alcohols can also be formed through a substitution reaction with a **haloalkane**. In the example given in Figure 4.92 the haloalkane would be dissolved in water.

$$CH_3CH_2Cl + H_2O \longrightarrow CH_3CH_2OH + HCl$$

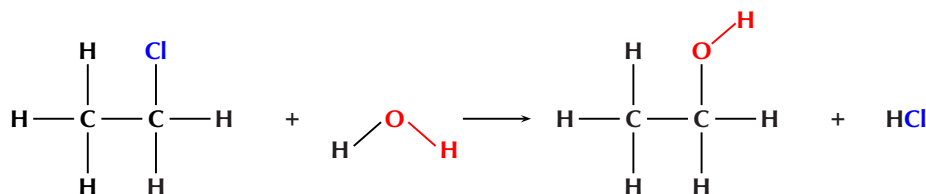



Figure 4.92: The formation of *ethanol* from *chloroethane* through a substitution reaction with water.

   Using a base (e.g. KOH, NaOH) dissolved in water and warming the solution would increase the rate of the reaction (Figure 4.93). However, in order for substitution to occur the following reaction conditions must be used:

   - low temperatures (around room temperature)
   - a dilute solution of a strong base (e.g. NaOH)
   - the solution must be aqueous (in water)

$$CH_3CH_2Br + KOH \longrightarrow CH_3CH_2OH + KBr$$

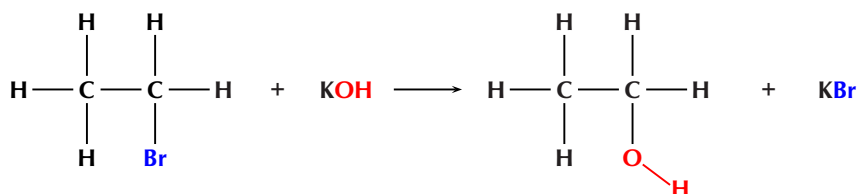



Figure 4.93: The formation of *ethanol* from *bromoethane* through a substitution reaction with potassium hydroxide (KOH).

   If the concentration of the base is too high then the halogen atom and a hydrogen atom could be eliminated (dehydrohalogenation).

3. **Formation of haloalkanes from alkanes**

   Another way of forming a haloalkane involves the removal of a hydrogen atom from a **saturated compound**. The hydrogen atom is replaced by a **halogen** (F, Cl, Br or I) to form a haloalkane (Figure 4.94). As alkanes are not very reactive light is needed for this reaction to take place.

**FACT**
Refer to the section on saturated and unsaturated structures for more information on why alkanes are not very reactive.

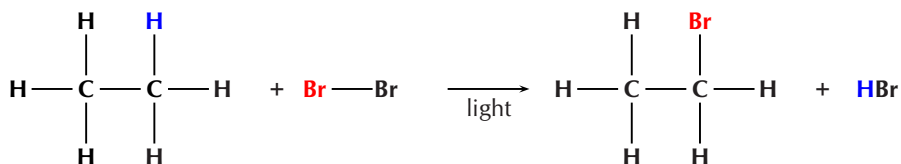



Figure 4.94: The formation of *bromoethane* from *ethane* through a substitution reaction with $Br_2$.

Reaction conditions:

- energy in the form of light

**Exercise 4 – 28: Substitution reactions**

1. When forming haloalkanes through a substitution reaction with alcohols is it best to use a tertiary, secondary or primary alcohol? Give a reason for your answer.
2. a) What is a substitution reaction?
   b) Write the general equation for a substitution reaction using the reactants WX and YZ
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

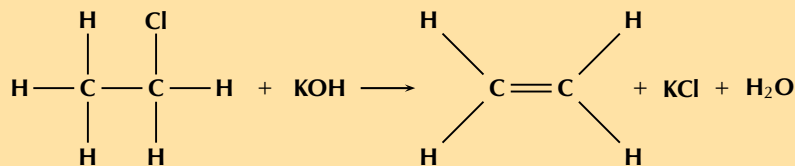
Check answers online with the exercise code below or click on 'show me the answer'.

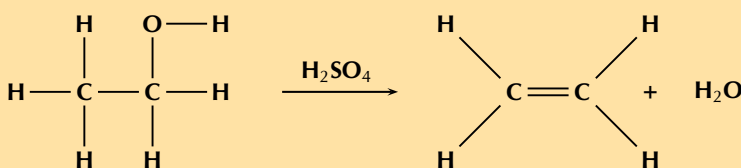
1\. 27PZ  2. 27Q2

**Exercise 4 – 29: Addition, elimination and substitution reactions**

1. a) Answer the following questions about hydration reactions:
      i. What type of reaction is a hydration reaction?
      ii. What is the most common catalyst used in this reaction?
   b) Name one of the most common catalysts used in a hydrogenation reaction.
   c) Answer the following questions about alkane reactions
      i. Are alkanes reactive compared to alkenes and alkynes?
      ii. In a haloalkane reaction an alkane and a halogen react. What condition is necessary for this reaction to take place?
   d) Look at the general equations given below and answer the questions that follow:
      i. haloalkane + base → **A** + **B**
         A. Name A and B for a hydrolysis reaction.
         B. What type of reaction is a hydrolysis reaction?
      ii. haloalkane + base → **A** + **B** + **C**
         A. Name A, B and C for a dehydrohalogenation reaction.
         B. What type of reaction is a dehydrohalogenation reaction?
      iii. Fill in the reaction conditions required for dehydrohalogenation and hydrolysis reactions in the table below:

| | **Dehydrohalogenation** | **Hydrolysis** |
|---|---|---|
| **Temperature** | | |
| **Solvent** | | |
| **Concentration of base** | | |

2. Refer to the diagram and then answer the questions that follow:

a) What type of reaction is this reaction?
b) Give a reason for your answer above.
c) What are the required reaction conditions?

3. Write the equation for the following reactions using the condensed structural representation. Say what type of reaction they are:
   a) The dehydration of hexan-2-ol ($CH_3CH(OH)CH_2CH_2CH_2CH_3$)
   b) The hydration of pent-1-ene ($CH_2CHCH_2CH_2CH_3$)
   c) The hydrolysis of 2-fluorobutane ($CH_3CH(F)CH_2CH_3$) with water (no base).
4. The following reaction takes place:

   a) What type of reaction is this?
   b) Give a reason for your answer.
5. Write the equations for the following reactions using condensed structural representations. State the type of reaction as well.
   a) The hydrogenation of propene ($CH_2CHCH_3$)
   b) The formation of a haloalkane from:
      i. butan-1-ol ($CH_2(OH)CH_2CH_2CH_3$) and hydrochloric acid (HCl)
      ii. 2-methylpent-2-ene ($CH_3C(CH_3)CHCH_2CH_3$) and hydroiodic acid (HI). Indicate the major and minor products and give reasons.
   c) Write balanced equations for the following reactions involving hept-3-ene ($CH_3CH_2CHCHCH_2CH_2CH_3$) and name the product.
      i. Hydrohalogenation, choose any halogen
      ii. The dehydrohalogenation with potassium hydroxide (KOH) of the product from c) i
      iii. Halogenation, choose any halogen
      iv. The dehydrohalogenation of the product from c) iii
6. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1a. 27Q3 1b. 27Q4 1c. 27Q5 1d. 27Q6 2. 27Q7 3. 27Q8
4. 27Q9 5. 27QB

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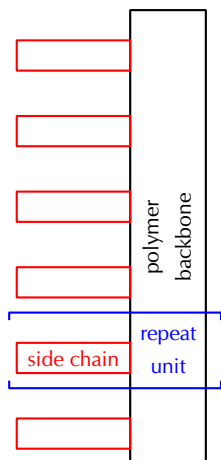
**FACT**
**Mono** means one, while **poly** means many. So a monomer is the single unit, and a polymer is made from many monomers.

**TIP**
A polymer consists of a backbone, made up of repeating units.

**FACT**
A thermoplastic is a plastic that can be heated and molded multiple times without changing chemically.

# 4.7 Plastics and polymers ESCM4

## What is a polymer? ESCM5

Polymers are large molecules (macromolecules) that are made up of many repeating structural units called **monomers** which have various functional groups. To put it more simply, a monomer is like a building block.

**DEFINITION:** *Monomer*

A monomer is a small molecule that can be combined through a reaction to form a polymer. It is a repeating unit in the polymer.

When lots of monomers are joined together by covalent bonds, they form a **polymer**.

**DEFINITION:** *Polymer*

Polymer is a term used to describe large molecules consisting of repeating structural units (monomers) connected by covalent chemical bonds.

In an **organic polymer**, the monomers are joined by the *carbon* atoms of the polymer backbone or *chain*. A polymer can also be **inorganic**, in which case there may be atoms such as *silicon* in the place of carbon atoms. We will look solely at organic polymers. Polymers are a specific group of *macromolecules*. A macromolecule is any compound with a large number of atoms. A *biological macromolecule* is one that is found in living organisms. Biological macromolecules include molecules such as carbohydrates, proteins, nucleic acids and lipids. They are essential for all known forms of life to survive.

**DEFINITION:** *Macromolecule*

A macromolecule is any molecule containing a large number of atoms.

The key feature that makes a polymer different from other macromolecules is the repetition of identical or similar monomers in the polymer chain. Polymers will contain chains of the same type of functional group and that functional group is dependent on the monomer used. The examples given over the following pages will help to make these concepts clearer. *Plastics* are a group of polymers that can be molded during manufacture. They can be one polymer or a blend (mixture) of polymers and may contain other substances as well. These other substances can be inorganic (e.g. used for electronic packaging) or stabilising (e.g. used for increasing fire resistance).

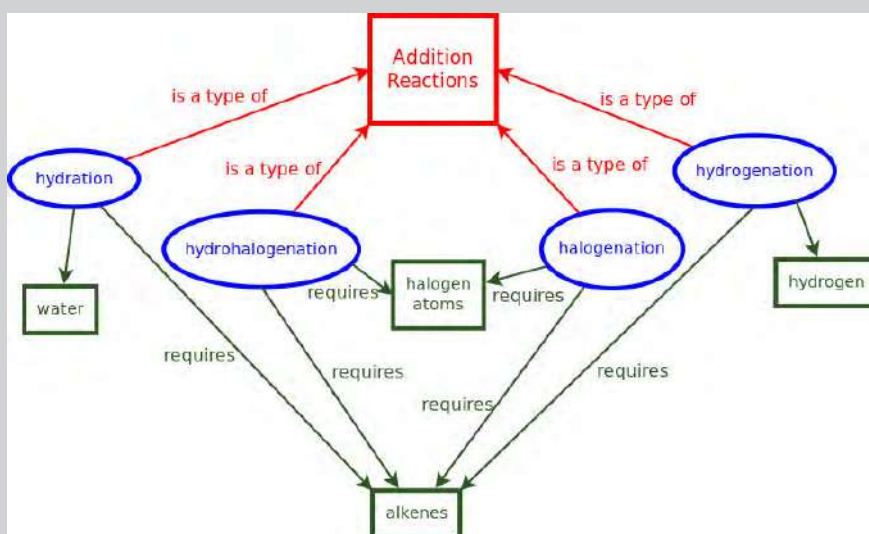
**DEFINITION:** *Plastic*

A subgroup of organic polymers that can be molded. Plastics may contain more than one organic polymer as well as other additives.

**Activity: What is a polymer?**

1. SASOL polymers is the largest division of the Johannesburg based companies' chemical business. Divide the class into 4 groups and have each group research the production of polymers in South Africa, including investigations into one of the products listed below:
   - Kevlar and Mylar
   - Break pads
   - Windscreens
   - Polymers to replace glass

   Research the functions of the materials, who invented or discovered them, and what they are made of. Present your findings to the rest of the class in a five minute discussion.
2. Read this section (What is a polymer?) carefully. Research any concepts you don't understand and draw up a concept map (mindmap) describing what a polymer is.

   *A concept map is a way of showing concepts and linking knowledge using graphics.* An example is given below:

## How do polymers form? ESCM6

Polymers are formed through a process called **polymerisation**, where monomers react together to form a polymer chain. Two of the types of polymerisation reactions are **addition polymerisation** and **condensation polymerisation**.

**DEFINITION:** *Polymerisation*

Polymerisation is a process of bonding monomers, or *single units* together to form longer chains called polymers.

### Addition polymerisation

In this type of reaction, **monomer molecules** are added to a growing **polymer chain** one at a time. (No *small molecules are eliminated* in the process).

Four major examples of addition polymers are polyethylene, polypropylene, polyvinylchloride (PVC) and polystyrene (Table 4.18). All four of these organic polymers are also plastics.

| Polymer name | Production (metric tons) | Some uses | | |
|---|---|---|---|---|
| polyethylene | >80 million | plastic bags | bottles | plastic films |
| polypropylene | >45 million | labelling | textiles | stationery |
| polyvinyl chloride | >30 million | construction | clothing | insulation |
| polystyrene | >2 million | packaging | molds | cutlery |

Table 4.18: Common uses of four major polymers formed through addition reactions.

1. **Polyethene (polyethylene)**

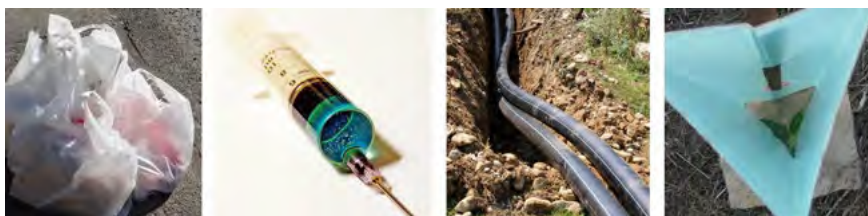



Figure 4.95: A collection of products made from polyethylene: plastic bags, a syringe, pipes, a plastic tree guard.

Earlier in this chapter we looked at the structure of a group of hydrocarbons called the *alkenes*. One example is the molecule **ethene**. The structural formula of ethene is shown in Figure 4.96. When lots of ethene molecules bond together, a polymer called **polyethene** (commonly called polyethylene) is formed. Ethene is the *unsaturated monomer* which, when joined to other ethene molecules through an addition reaction, forms the *saturated polymer* **polyethene**.

Polyethene is the most common plastic with over 80 million metric tons produced each year. It is commonly known as polyethylene. It is cheap and is used to make squeeze bottles, plastic bags, films, toys and molded objects as well as electric insulation. It has a recycling number 4 which means that it is easy to process, has strength, toughness, flexibility, is easy to seal and has a barrier to moisture.

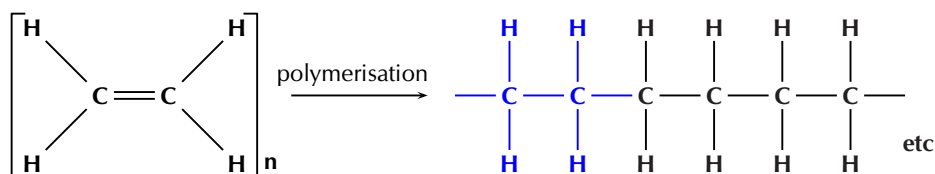



Figure 4.96: The polymerisation of an **ethene** monomer to form a **polyethene** polymer. The repeat unit is highlighted in blue.

A polymer may be a chain of thousands of monomers, and so it is impossible to draw the entire polymer. Rather, the structure of a polymer can be condensed and represented as shown in Figure 4.97.

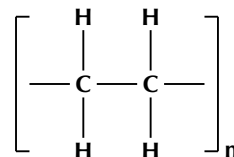



Figure 4.97: A simplified representation of polyethene.

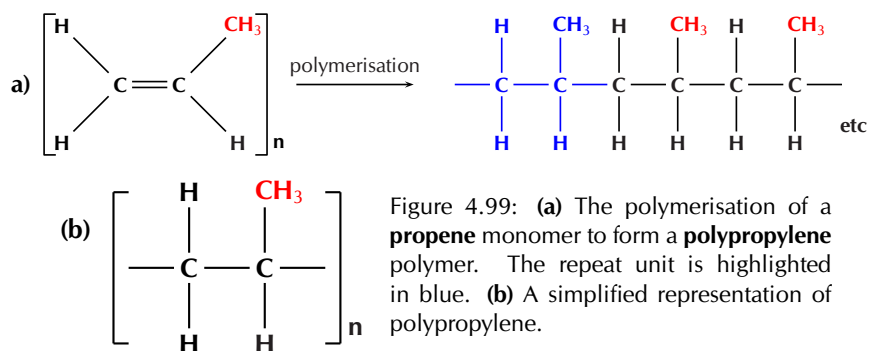
The monomer is enclosed in brackets and the $n$ represents the number of **repeating units** (the saturated form of the monomer) in the polymer, where $n$ is any whole number. What this shows is that the monomer is repeated an indefinite number of times in a molecule of polyethene.

See video: 27QC at www.everythingscience.co.za

2. **Polypropene (polypropylene)**

Figure 4.98: A collection of products made from polypropylene: a lamp cover, computer parts, and shopping trolleys.

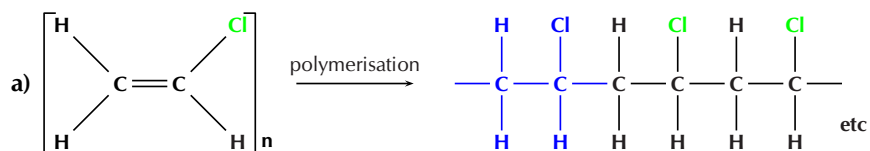
Another example of a polymer is *polypropene* (Figure 2). Polypropene (commonly known as polypropylene) is also a plastic, but is stronger than polyethene and is used to make crates, fibres and ropes as well as being used in textiles, stationery and car parts. In this polymer, the monomer is the alkene called **propene**.

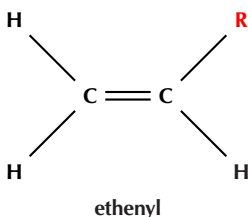
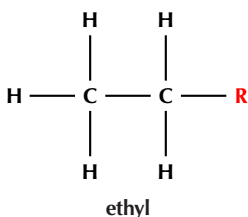
Figure 4.99: **(a)** The polymerisation of a **propene** monomer to form a **polypropylene** polymer. The repeat unit is highlighted in blue. **(b)** A simplified representation of polypropylene.

See video: 27QD at www.everythingscience.co.za

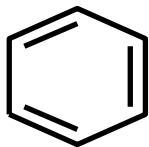
3. **Polyvinyl chloride (PVC)**

Figure 4.100: A collection of products made from polyvinyl chloride: pipes, electrical tape, and car parts.

Polyvinyl chloride or *PVC* (Figure 4.101) is formed from the monomer chloroethene, which is commonly known as vinyl chloride. PVC is used in construction, especially plastic piping. With the addition of a plasticiser it is also used in clothing and upholstery and to replace rubber. The role of the plasticiser is to increase the ability of a material to change shape without breaking.

a)
H
Cl
C=C
H
H
n
polymerisation
H Cl H Cl H Cl
—C—C—C—C—C—C—
H H H H H H
etc

**TIP**

**Ethenyl** is not the same as ethyl. Ethyl is an ethane molecule bonded to another compound (**R**). Ethenyl is an ethene molecule bonded to another compound (**R**).

**FACT**

Benzene can be represented with three double bonds:

or with a circle inside the ring:

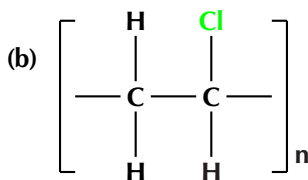
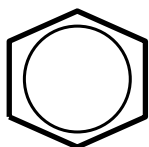



Figure 4.101: **(a)** The polymerisation of a **chloroethane** monomer to form a **polyvinyl chloride** polymer. The repeat unit is highlighted in blue. **(b)** A simplified representation of polyvinyl chloride.

See video: 27QF at www.everythingscience.co.za

4. **Polyvinyl acetate**

Polyvinyl acetate or *PVA* (Figure 4.103) is formed from the monomer ethenyl ethanoate, which is commonly known as vinyl acetate. PVA is used in various glues and adhesives (such as wood glue).

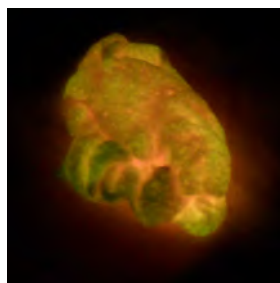



Figure 4.102: Glowing slime made with polyvinyl acetate.

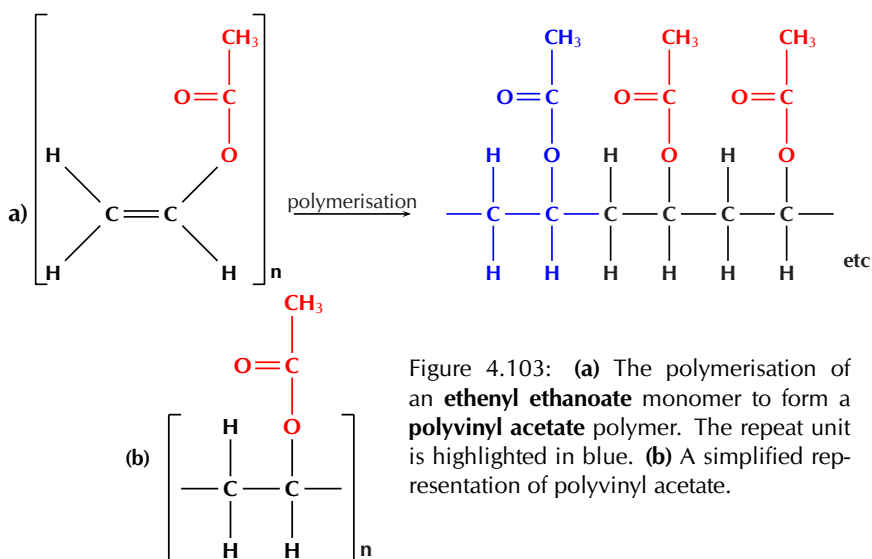
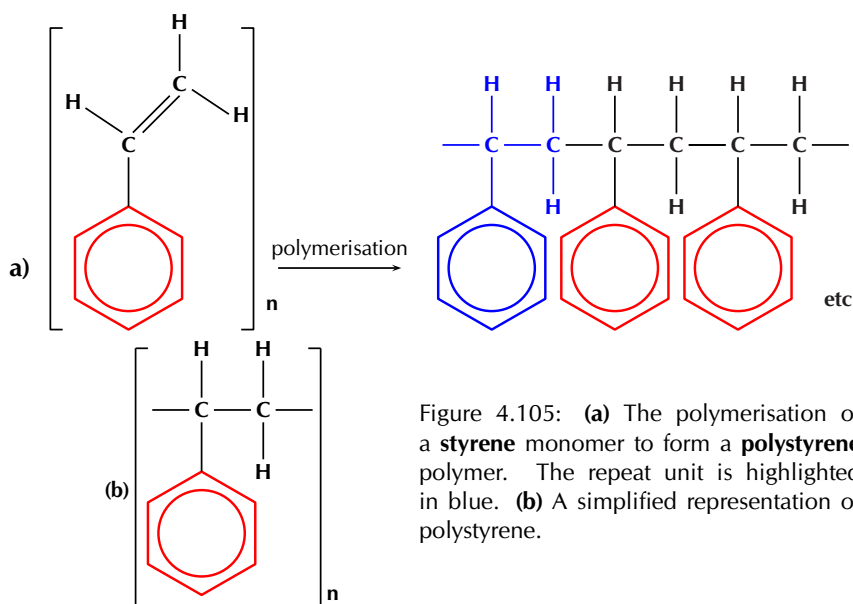



Figure 4.103: **(a)** The polymerisation of an **ethenyl ethanoate** monomer to form a **polyvinyl acetate** polymer. The repeat unit is highlighted in blue. **(b)** A simplified representation of polyvinyl acetate.

5. **Polystyrene**

Figure 4.104: A collection of products made from polystyrene: a cup, a guitar case, polystyrene carvings, and floating pool noodles.

*Polystyrene* is made from the monomer *styrene* which is a liquid petrochemical. Styrene consists of a benzene ring (a six membered ring with three double bonds) bonded to an ethene chain. Polystyrene is an aromatic polymer and has many uses including protective packaging, in trays, as plastic lids and bottles.

Figure 4.105: **(a)** The polymerisation of a **styrene** monomer to form a **polystyrene** polymer. The repeat unit is highlighted in blue. **(b)** A simplified representation of polystyrene.

**FACT**
Remember that the IUPAC name of:

- ethylene is ethene
- propylene is propene
- vinyl chloride is chloroethene

See video: 27QG at www.everythingscience.co.za

It is interesting to note that the polymerisation of a monomer leads to different physical properties of the polymer (Table 4.19). For the polymers the melting points are dependent on the polymer grade.

| Name | Melting point (°C) | Boiling point (°C) | Phase (at 25°C) |
|---|---|---|---|
| ethylene | -169,2 | -103,7 | gas |
| polyethylene | 105 - 130 | does not boil | solid |
| propylene | -185,2 | -47,6 | gas |
| polypropylene | 130 - 171 | does not boil | solid |
| vinyl chloride | -153,8 | -13,4 | gas |
| polyvinyl chloride | 100 - 260 | does not boil | solid |
| vinyl acetate | -93 | 72,7 | liquid |
| polyvinyl acetate | 60 | does not boil | solid |
| styrene | -30 | 145 | liquid |
| polystyrene | 240 | does not boil | solid |

Table 4.19: Different physical properties of addition monomers and polymers.

### Activity: Development of addition polymers

Polyethene was discovered by accident, twice. Look into the history of this commonly used plastic as well as other addition polymers.

- Who discovered them?
- How were they discovered?
- What difference have they made to modern life?

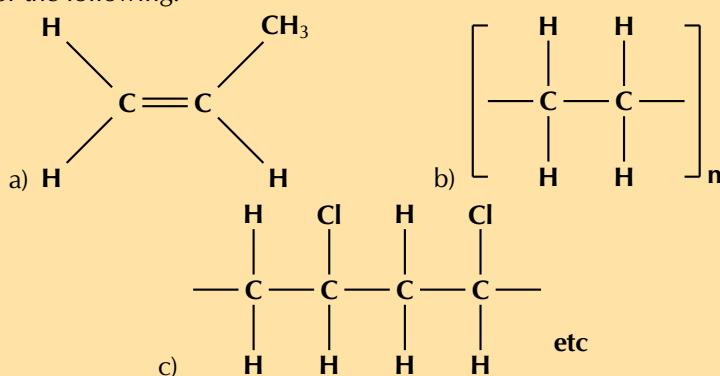
### Activity: Building polymers

Using atomic model kits, jelly tots, or playdough and toothpicks build four ethene monomers, four propene monomers and four vinyl chloride monomers.

- Join three of each type of monomer to form polyethene, polypropene and polyvinyl chloride.
- Identify the repeating unit in each polymer.
- List the differences and similarities between the monomers and the repeating unit.

Note that the monomers all contain double bonds, while the repeating unit has only a single bond.

**Exercise 4 – 30: Addition polymers**

1. What trend is visible when comparing the melting points of monomers and their polymers?
2. Name the monomer (where polymer is given) or polymer (where monomer is given) for the following:

3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27QH   2. 27QJ

**Condensation polymerisation**

In this type of reaction, two monomer molecules combine by means of a covalent bond, and a small molecule such as water is lost in the bonding process. Nearly all biological macromolecules are formed using this process. **Polyesters** are polymers that form through condensation polymerisation.

Polyesters have a number of characteristics which make them very useful. They are resistant to stretching and shrinking, they are easily washed and dry quickly, and they are resistant to mildew. It is for these reasons that polyesters are being used more and more in **textiles**. Polyesters are stretched out into fibres and can then be made into fabric and articles of clothing. In the home, polyesters are used to make clothing, carpets, curtains, sheets, pillows and upholstery.

Polyesters are a group of polymers that contain the **ester** functional group in their main chain. This bond is called an **ester linkage**. For a polyester however there needs to be continuation of the chain. This requires a *-diol* (two alcohol functional groups) and a *diacid* (two carboxylic acid functional groups) as shown in Figure 4.106, or a monomer that contains both a hydroxyl group and a carboxylic acid.

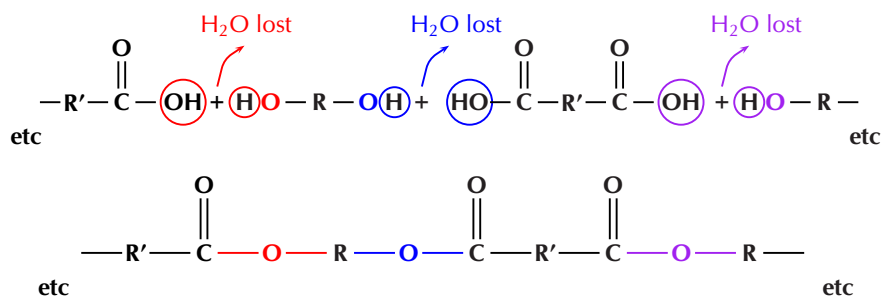



Figure 4.106: The propagation of the **ester linkage** in a **polyester**.

**FACT**
Polyethylene terephthalate (PET) is not just a textile. PET is in fact a plastic which can also be used to make plastic drink bottles. Many drink bottles are recycled by being reheated and turned into polyester fibres. This type of recycling helps to reduce disposal problems.

1. **Polyethylene terephthalate (PET)**

Figure 4.107: A collection of products made from polyethylene terephthalate: sailcloth and plastic squeeze bottles.

Although there are many forms of polyesters, the term *polyester* usually refers to *polyethylene terephthalate (PET)*. PET is made from ethan-1,2-diol (ethylene glycol, an alcohol) and terephthalic acid (a carboxylic acid). In the reaction, a hydrogen atom is lost from the alcohol, and a hydroxyl group is lost from the carboxylic acid. Together these form one water molecule which is lost during condensation reactions. A new bond is formed between an oxygen and a carbon atom. This bond is called an **ester linkage**. The reaction is shown in Figure 4.108.

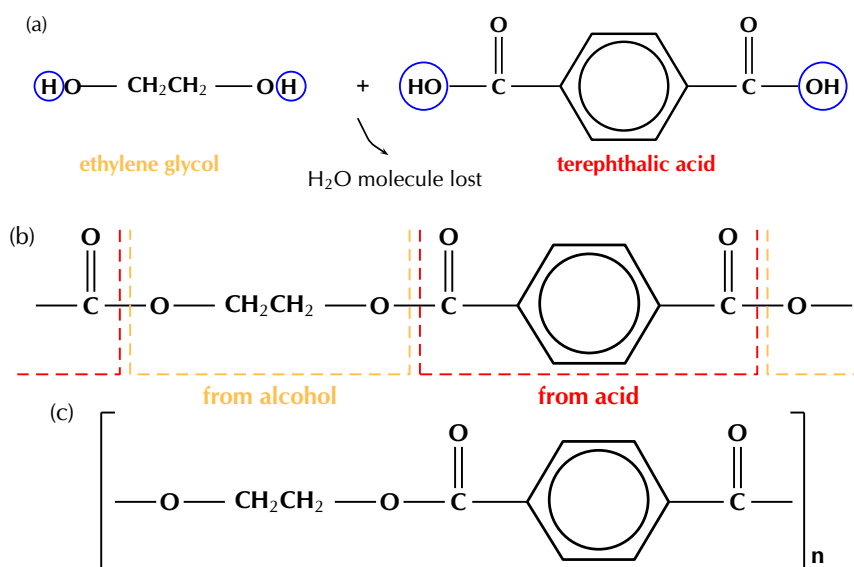



Figure 4.108: **(a)** Ethylene glycol (alcohol) and terephthalic acid (carboxylic acid) monomers react to form **(b)** the polymer poly(ethylene terephthalate) (PET). **(c)** A simplified representation of PET.

See video: 27QK at www.everythingscience.co.za

**FACT**
3D printing is the process of printing a solid, three-dimensional object. If you have a 3D printer it is possible to print objects ranging from fashion items (e.g. cell phone covers), to human organs, although organs require living cells as the 'ink'.

2. **Polylactic acid (PLA)**

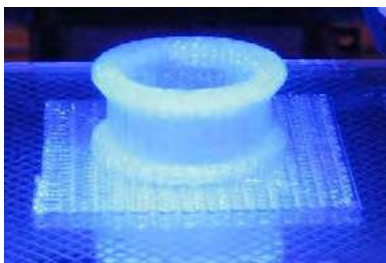



Figure 4.109: 3-D printing using polylactic acid as the *ink*.

Despite the name, polylactic acid (PLA) is actually a polyester (look for the ester linkage we spoke about before). It is an interesting polymer because the monomer used for this polymer (Figure 4.110) comes from the biological fermentation of plant materials, while most monomers used in plastics come from petroleum. As a result PLA is biodegradable and has low carbon dioxide ($CO_2$) emissions.

as alcohol
as carboxylic acid

from 'alcohol'
from 'carboxylic acid'

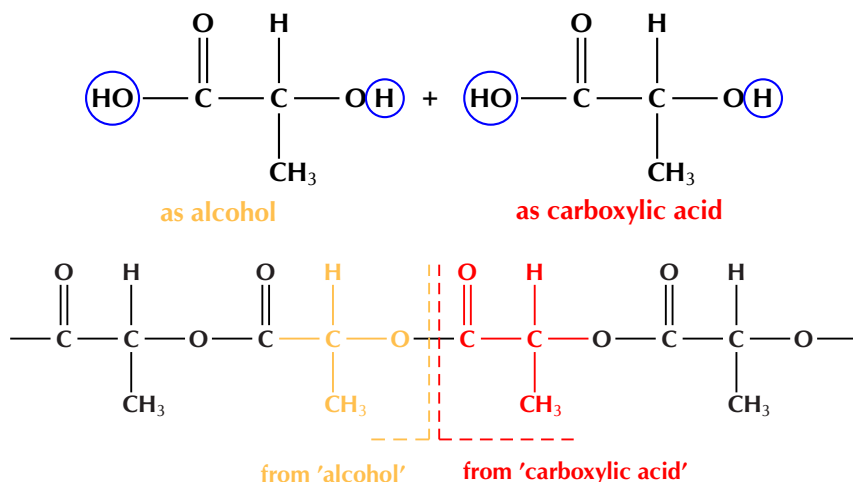



Figure 4.110: **Ester linkages** between lactic acid monomers.

PLA is mostly used for packaging material and, because it is biodegradable, it has the potential to alleviate land-fill disposal problems. The PLA polymer structural repeat unit is given in Figure 4.111.

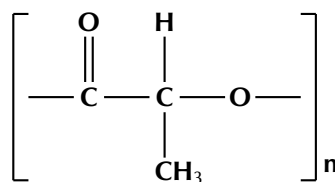



Figure 4.111: The polyester *polylactic acid*.

See video: 27QM at www.everythingscience.co.za

| Polymer name | Some uses | | |
|---|---|---|---|
| polyethylene terephthalate | synthetic fibre | plastic containers | resins |
| polylactic acid | medical implants | packaging | textiles |

Table 4.20: Some common uses of polymers formed through condensation reactions.

For polyethylene terephthalate there are two monomers *ethylene glycol* and *terephthalic acid* that join to form the polymer. Each monomer has its own unique properties (Table 4.21).

| Name | Monomer/ polymer | Melting point (°C) | Boiling point (°C) | Phase (at 25°C) |
|---|---|---|---|---|
| terephthalic acid | monomer | 300 | sublimes (solid → gas) | solid |
| ethylene glycol | monomer | -12,9 | 197,3 | liquid |
| polyethylene terephthalate | polymer | >250 | decomposes | solid |
| lactic acid | monomer | 16,8 | 122 | liquid |
| polylactic acid | polymer | 150 - 160 | does not boil | solid |

Table 4.21: Different physical properties of condensation monomers and polymers.

**Exercise 4 – 31: Condensation polymers**

1. What is the main difference between the reactants used in an addition polymerisation and those used in a condensation polymerisation?
2. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27QN

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**Extension**

Initiation, propagation and termination

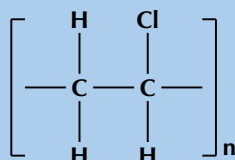
There are three stages in the process of addition polymerisation. **Initiation** refers to a chemical reaction that triggers the first reaction. In other words, initiation is the starting point of the polymerisation reaction. **Chain propagation** is the part where monomers are continually added to form a longer and longer polymer chain. During chain propagation it is the reactive end groups of the polymer chain that react in each propagation step to add a new monomer to the chain. Once a monomer has been added the reactive part of the polymer is now in this last monomer unit so that propagation will continue. **Termination** refers to a chemical reaction that destroys the reactive part of the polymer chain so that propagation stops.

It is important to be able to identify the monomer used to produce a polymer from the repeat unit of the chain.

**Worked example 32: Identifying monomers**

***QUESTION***

Which monomer was used to make this polymer (give the name and draw the structure):

$$\left[ -\overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}} - \overset{\displaystyle Cl}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}} - \right]_n$$

***SOLUTION***

**Step 1: Identify the polymer through functional groups**

This polymer contains a chlorine atom. Which polymers contain chlorine? Polyvinyl chloride contains chlorine.

**Step 2: Consider what you know of this polymer**

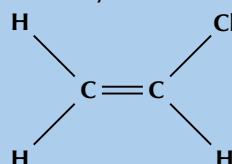
PVC forms through an addition reaction. There are two carbon atoms in the repeat unit (ethane) and the polymer contains chlorine atoms.

**Step 3: Apply this knowledge to the monomer**

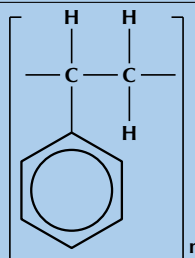
An addition reaction indicates that the monomer must contain a double bond. As the polymer contains units of ethane the monomer must be an ethene. The monomer must contain a chlorine atom.

**Step 4: Name the monomer**

The monomer must be **chloroethene** also known as **vinyl chloride**

**Step 5: Draw the structure of this monomer**

**Worked example 33: Identifying monomers**

***QUESTION***

Which monomer was used to make this polymer (give the name and draw the structure):

***SOLUTION***

**Step 1: Identify the polymer through functional groups**

This polymer contains a benzene ring connected to two carbon atoms. Which polymers contain a benzene ring? Polystyrene contains a benzene ring connected to two carbon atoms.

**Step 2: Consider what you know of this polymer**

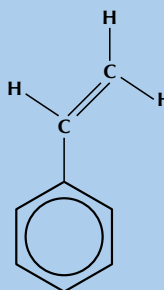
Polystyrene forms through an addition reaction. There are two carbon atoms attached to the benzene ring.

**Step 3: Apply this knowledge to the monomer**

An addition reaction means that the monomer must contain a double bond. The polymer contains two carbon atoms attached to the benzene ring which must be connected by a double bond in the monomer.

**Step 4: Name the monomer**

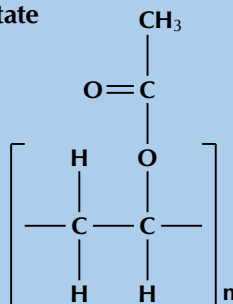
The monomer must be **styrene**.

**Step 5: Draw the structure of this monomer**

## Worked example 34: Identifying monomers

***QUESTION***

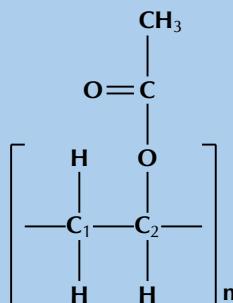
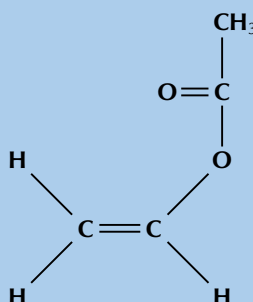
Give the structure of the monomer used to make polyvinyl acetate:

***SOLUTION***

**Step 1: Draw the repeat unit structure of polyvinyl acetate**

**Step 2: Consider what you know of this polymer**

Polyvinyl acetate must form from vinyl acetate.
The IUPAC name of vinyl acetate is ethenyl ethanoate.
The polymer forms through an addition reaction.

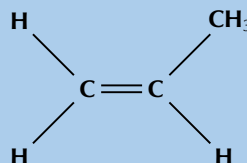
**Step 3: Apply this knowledge to the monomer**

An addition reaction means that the monomer must contain a double bond. The only place this bond can occur is between carbon 1 and carbon 2:

**Step 4: Draw the structure of the monomer**

## Worked example 35: Identifying polymers

***QUESTION***

Which polymer is formed from propene? Give the name and repeat structural unit.

***SOLUTION***

**Step 1: Draw the structural representation of the monomer**

**Step 2: Consider what you about this monomer**

Propene contains a double bond between the first and second carbon atoms.

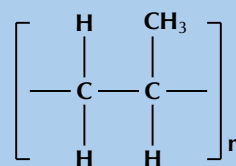
**Step 3: Apply this knowledge to the polymer**

The polymer must form through an addition reaction by breaking the double bond. There must be a methyl group on every second carbon atom.

**Step 4: Name the polymer**

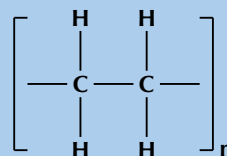
The polymer must be **polypropene** (polypropylene).

**Step 5: Draw the repeat structural unit of this polymer**

```
 ┌   H    CH3 ┐
     |    |
 | ─ C ── C ─ |
     |    |
 └   H    H   ┘n
```

### Worked example 36: Identifying types of polymerisation reactions

***QUESTION***

Was an addition or a condensation reaction used to make this polymer?

```
 ┌   H    H   ┐
     |    |
 | ─ C ── C ─ |
     |    |
 └   H    H   ┘n
```

***SOLUTION***

**Step 1: Look at the types of bonds and functional groups in the polymer repeat unit**

There are only single carbon-carbon bonds, there are no functional groups.

**Step 2: What type of monomer could this polymer have formed from?**

As there are no oxygen atoms in the repeat unit, this polymer could only have formed from a monomer containing a double bond.

**Step 3: Apply this knowledge to determine the type of reaction**

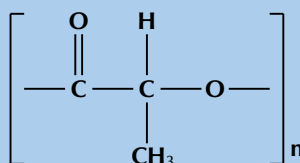
This polymer must have formed through an **addition** reaction.

(This is polyethene and was formed by the addition of ethene monomers)

### Worked example 37: Identifying types of polymerisation reactions

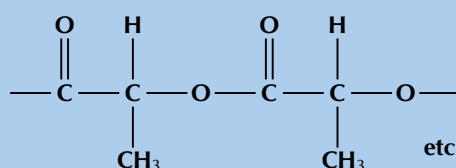
***QUESTION***

Was an addition or a condensation reaction used to make this polymer?

```
 ┌   O    H        ┐
     ‖    |
 | ─ C ── C ── O ─ |
          |
 └        CH3      ┘n
```

***SOLUTION***

**Step 1: Look at the types of bonds in the polymer repeat unit**

There are carbon-carbon single bonds. If you expand the repeating unit you can see that there is an ester linkage in the structural chain.

```
   O    H         O    H
   ‖    |         ‖    |
 ─ C ── C ── O ── C ── C ── O ─
        |              |
        CH3            CH3       etc
```

**Step 2: What type of monomer could this polymer have formed from?**

The ester linkage requires an alcohol and a carboxylic acid monomer or a monomer that contains both a hydroxyl and carboxyl functional group.

**Step 3: Apply this knowledge to determine the type of reaction**

The reaction of an alcohol and carboxylic acid to form an ester linkage (and resulting in the loss of water) is a **condensation** reaction.

(This is polylactic acid and was formed by the condensation reaction of lactic acid monomers)

**Experiment: Making polymer slime**

**Aim:**

To compare the differences in slime made from polyvinyl alcohol and polyvinyl acetate.

**Apparatus:**

- 4% aqueous polyvinyl alcohol solution, 4% aqueous borax (hydrated sodium tetraborate) solution, white glue (polyvinyl acetate), food colourant
- a beaker, two disposable plastic cups, a metal spatula, disposable plastic gloves

**Method:**

1. Place 40 $cm^3$ of the polyvinyl alcohol solution in one plastic cup and label it *A*.
2. Place 20 $cm^3$ of the white glue in the second cup. Add 20 $cm^3$ of water and stir. Label this cup *B*.
3. Add one drop of food colourant to each cup and stir well.
4. Measure out 10 $cm^3$ of the borax solution into the beaker, then add to cup A.
5. Repeat step 4 with cup B.
6. Stir until gelling is complete (i.e. the slime).
7. Put on the disposable plastic gloves, take the slime out of cup A and roll it around in your hand to remove air bubbles, repeat with the slime in cup B.

**Questions:**

1. Pull each slime apart slowly, what happens?
2. Pull each slime apart quickly, what happens?
3. Roll each slime into a ball and drop it onto the bench, what happens?
4. Place a small bit of each slime on the bench and hit it hard with your hand, what happens?
5. What are the similarities and differences between the two slimes?

**Discussion and Conclusions:**

You should find that the slime does not break under slow stress, but will break if you pull it apart too quickly. This is because the slime can expand under stress. It should even bounce slightly if you throw it onto a hard surface.

## Impact of polymers and plastics ESCM7

### Plastics and the environment

Although plastics have had a huge impact globally, there is also an environmental price that has to be paid for their use. The following are just some of the ways in which plastics can cause damage to the environment.

**FACT**
The Great Pacific Garbage Patch is a large area of waste that has collected in the central North Pacific Ocean. It is estimated to cover at least 700 000 km$^2$.

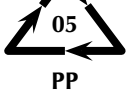
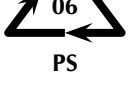
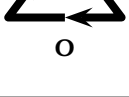
1. **Waste disposal**
   Plastics are not easily broken down by micro-organisms and therefore most are not easily biodegradeable. This leads to waste disposal problems.
2. **Air pollution**
   When plastics burn, they can produce toxic gases such as carbon monoxide, hydrogen cyanide and hydrogen chloride (particularly from PVC and other plastics that contain chlorine or nitrogen).
3. **Recycling**
   It is difficult to recycle plastics because each type of plastic has different properties and so different recycling methods may be needed for each plastic. Some plastics can be remelted and re-used, while others can be ground up and used as a filler. One of the problems with recycling plastics is that they have to be sorted according to plastic *type*. A list of some of the different types and their identification codes are given in Table 4.22. Alternatively, plastics should be re-used. In many countries, including South Africa, shoppers must now pay for plastic bags. This encourages people to collect and re-use the bags they already have.

| PIC | Plastic type | Properties | Uses | Recycling |
|---|---|---|---|---|
| 01 PET | polyethylene terephthalate | very clear<br>high strength<br>barrier to gas<br>barrier to moisture | water bottles<br>peanut butter jars<br>mouthwash bottles | can recycle most places |
| 02 PE-HD | high-density polyethylene | very stiff<br>high strength<br>barrier to moisture<br>allows gas through | yoghurt tubs<br>detergent bottles<br>cereal box liners | can recycle most places |
| 03 PVC | polyvinyl chloride | easily blended<br>high strength<br>very toughness | detergent bottles<br>medical equipment<br>piping | very rarely recycled |
| 04 PE-LD | low-density polyethylene | very flexible<br>high strength<br>barrier to moisture | clothing<br>squeeze bottles<br>bread bags | not often recycled |
| 05 PP | polypropylene | high strength<br>resistance to heat<br>barrier to moisture | syrup bottles<br>plastic caps<br>straws | fairly easy to recycle |
| 06 PS | polystyrene | many uses<br>very clear<br>is easily formed | egg cartons<br>disposable cups<br>take-away boxes | fairly easy to recycle |
| 07 O | other | dependent on combination of polymers | large containers<br>sunglasses<br>computer cases | often not recycled |

Table 4.22: The plastic identification code (PIC), type, properties and uses of various commonly used plastics.

**Case study: Plastic pollution in South Africa**

Read the following extract, taken from *Planet Ark* (September 2003), and then answer the questions that follow.

> *'South Africa launches a programme this week to exterminate its national flower - the millions of used plastic bags that litter the landscape.*
>
> *Beginning on Friday, plastic shopping bags used in the country must be both thicker and more recyclable, a move officials hope will stop people from simply tossing them away. 'Government has targeted plastic bags because they are the most visible kind of waste,' said Phindile Makwakwa, spokeswoman for the Department of Environmental Affairs and Tourism. 'But this is mostly about changing people's mindsets about the environment.'*
>
> *South Africa is awash in plastic pollution. Plastic bags are such a common eyesore that they are dubbed roadside daisies and referred to as the national flower. Bill Naude of the Plastics Federation of South Africa said the country used about eight billion plastic bags annually, a figure which could drop by 50 percent if the new law works.'*

It is difficult sometimes to imagine exactly how much waste is produced in our country every year. Where does all of this go to? You are going to do some simple calculations to try to estimate the volume of plastic packets that is produced in South Africa every year.

1. Take a plastic shopping packet and fold it until it forms a tightly compressed cube.
   a) Measure the approximate length, breadth and depth of your compressed plastic bag.
   b) Calculate the approximate volume that is occupied by the packet.
   c) Now calculate the approximate volume of your classroom by measuring its length, breadth and height.
   d) Calculate the number of compressed plastic packets that would fit into a classroom of this volume.
   e) If South Africa produces an average of 8 billion plastic bags each year, how many classrooms would be filled if all of these bags were thrown away and not re-used?
2. What has South Africa done to try to reduce the number of plastic bags that are produced?
3. Do you think this has helped the situation?
4. What can *you* do to reduce the amount of plastic that you throw away?
5. Take a survey of your classmates, family and friends on the quantities and types of solid waste they generate. What methods could they use to reduce that waste?
6. It has now been over *ten years* since shops started charging for plastic bags. Research the effects this law has had on South African plastic waste.

**Case study: Biodegradable plastics**

Read the following extract, taken from Nova: Science in the news (July 2006), and then answer the questions that follow.

> *Our whole world seems to be wrapped in plastic. Almost every product we buy, most of the food we eat and many of the liquids we drink come*

*encased in plastic. Plastic packaging provides excellent protection for the product, it is cheap to manufacture and seems to last forever. Lasting forever, however, is proving to be a major environmental problem. Another problem is that traditional plastics are manufactured from non-renewable resources - oil, coal and natural gas. In an effort to overcome these problems, researchers and engineers have been trying to develop biodegradable plastics that are made from renewable resources, such as plants.*

*The term biodegradable means that a substance can be broken down into simpler substances by the activities of living organisms, and therefore is unlikely to remain in the environment. The reason most plastics are not biodegradable is because their long polymer molecules are too large and too tightly bonded together to be broken apart and used by decomposer organisms. However, plastics based on natural plant polymers that come from wheat or corn starch have molecules that can be more easily broken down by microbes.*

*Starch is a natural polymer. It is a white, granular carbohydrate produced by plants during photosynthesis and it serves as the plant's energy store. Many plants contain large amounts of starch. Starch can be processed directly into a bioplastic but, because it is soluble in water, articles made from starch will swell and deform when exposed to moisture, and this limits its use. This problem can be overcome by changing starch into a different polymer. First, starch is harvested from corn, wheat or potatoes, then micro-organisms transform it into lactic acid, a monomer. Finally, the lactic acid is chemically treated to cause the molecules of lactic acid to link up into long chains or polymers, which bond together to form a plastic called polylactide (PLA).*

*PLA can be used for products such as plant pots and disposable nappies. It has been commercially available in some countries since 1990, and certain blends have proved successful in medical implants, sutures and drug delivery systems because they are able to dissolve away over time. However, because PLA is much more expensive than normal plastics, it has not become as popular as one would have hoped.*

**Questions:**

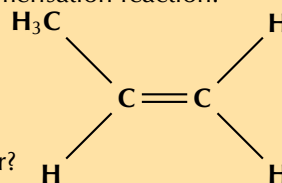
1. In your own words, explain what is meant by a *biodegradable plastic*.
2. Using your knowledge of chemical bonding, explain why some polymers are biodegradable and others are not.
3. Explain why lactic acid is a more useful monomer than starch, when making a biodegradable plastic.
4. If you were a consumer (shopper), would you choose to buy a biodegradable plastic rather than another? Explain your answer.
5. What do you think could be done to make biodegradable plastics more popular with consumers?

**Exercise 4 – 32: Polymers**

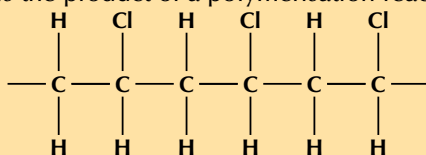
1. The following monomer is a reactant in a polymerisation reaction:

   $H_3C$ H

   C=C

   H H

   a) What is the IUPAC name of this monomer?

b) Give the structural representation of the polymer that is formed in this polymerisation reaction.
c) Is the reaction an addition or condensation reaction?

2. The polymer below is the product of a polymerisation reaction.

a) Give the structural formula of the monomer used to form this polymer.
b) What is the name of the monomer?
c) Draw the abbreviated structural formula for the polymer (the repeat unit).
d) Has this polymer been formed through an addition or condensation polymerisation reaction?

3. A polymerisation reaction takes place between two lactic acid monomers.
a) Give the structural representation for:
i. lactic acid
ii. the repeat unit of the polymer product
b) What is the name of the product?
c) Was this polymer formed through an addition or a condensation reaction?

4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27QP 2. 27QQ 3. 27QR

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## 4.8 Chapter summary ESCM8

See presentation: 27QS at www.everythingscience.co.za

See presentation: 27QT at www.everythingscience.co.za

- **Organic chemistry** is the branch of chemistry that deals with organic molecules. An **organic molecule** is one that contains carbon.
- All **living organisms** contain carbon. Plants use sunlight to convert carbon dioxide in the air into organic compounds through the process of **photosynthesis**. Animals and other organisms then feed on plants to obtain their own organic compounds. **Fossil fuels** are another important source of carbon.
- It is the **unique properties of the carbon atom** that give organic compounds certain properties.
- The carbon atom has **four valence electrons**, so it can bond with many other atoms, often resulting in long chain structures. It also forms mostly **covalent bonds** with the atoms that it bonds to.
- An organic compound can be represented in different ways, using its **molecular formula**, **structural formula**, **semi-structural formula** or **condensed structural formula**.
- A **functional group** is a particular group of atoms within a molecule, which give it certain reaction characteristics. Organic compounds can be grouped according to their functional group.
- The **hydrocarbons** are organic compounds that contain only carbon and hydro-

gen. They can be further divided into the alkanes, alkenes and alkynes, based on the type of bonds between the carbon atoms.

- The **alkanes** have only **single bonds** between their carbon atoms and are unreactive. The **alkenes** have at least one **double bond** between two of their carbon atoms and the **alkynes** have at least one **triple bond** between two of their carbon atoms. They are both more reactive than the alkanes.
- An **alcohol** is an organic compound that contains a **hydroxyl group** ($-OH$).
- The alcohols have a number of different uses including their use as a solvent, for medicinal purposes and in alcoholic drinks.
- The alcohols share a number of **properties** because of the hydroxyl group. The hydroxyl group affects the **solubility** of the alcohols (in water). Those with shorter carbon chains are generally more soluble, and those with longer chains are less soluble. The strong hydrogen bond between the hydrogen and oxygen atoms in the hydroxyl group gives alcohols a higher melting point and boiling point than the hydrocarbons.
- A **carbonyl group** consists of an oxygen atom that is double-bonded to a carbon atom. In a **ketone** the carbonyl group is in the middle of the carbon chain. In an **aldehyde** the carbonyl group is at the end of the chain.
- The **carboxylic acids** are organic acids that contain a **carboxyl group** with the formula $-COOH$. In a carboxyl group a carbon atom is double-bonded to an oxygen atom, and it is also bonded to a hydroxyl group.
- The carboxylic acids have weak **acidic properties** because the hydrogen atom is able to dissociate from the carboxyl group.
- An **ester** is formed when an alcohol reacts with a carboxylic acid. Esters contain a carbonyl functional group as well as an oxygen atom bonded to the carbonyl carbon atom and another carbon atom.
- A molecule is said to be **saturated** if it contains the maximum possible number of hydrogen (or other) atoms for that molecule. The alkanes are all saturated compounds.
- A molecule is **unsaturated** if it does not contain the maximum number of hydrogen atoms for that molecule. The alkenes and alkynes are examples of unsaturated molecules. If a double or triple bond is broken, more hydrogen (or other) atoms can be added to the molecule.
- If two compounds are **isomers**, it means that they have the same molecular formulae but different structural formulae.
- Organic compounds are **named** according to their functional group and its position in the molecule, the number of carbon atoms in the molecule and the position of any double and triple bonds. The IUPAC rules for nomenclature are used in the naming of organic molecules.
- Many of the **properties** of the hydrocarbons are determined by their **molecular structure**, the **bonds** between atoms and molecules, and their **surface area**.
- The **melting points** and **boiling points** of the hydrocarbons increases as their number of carbon atoms increases.
- The **molecular mass** of the hydrocarbons determines whether they will be in the gaseous, liquid or solid phase at specific temperatures.
- The weaker the **intermolecular forces** between molecules the more **volatile** and the higher the **vapour pressure** of that compound. Haloalkanes become less volatile the more halogen atoms they contain. This is due to increased intermolecular forces.
- Three types of reactions that occur are **addition**, **elimination** and **substitution**. The alkenes undergo **addition** reactions because they are unsaturated.
- A **polymer** is a macromolecule that is made up of many repeating structural units

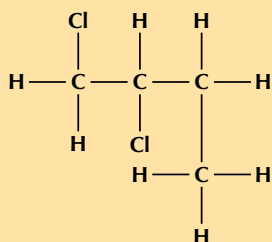
called **monomers**, which are joined by covalent bonds.

- Polymers that contain carbon atoms in the main chain are called **organic polymers**.
- Organic polymers can be divided into **natural organic polymers** (e.g. natural rubber) or **synthetic organic polymers** (e.g. polystyrene).
- The polymer **polyethene** for example, is made up of many ethene monomers that have been joined into a polymer chain.
- Polymers form through a process called **polymerisation**. Two examples of polymerisation reactions are **addition** and **condensation** reactions.
- An **addition polymerisation reaction** occurs when unsaturated monomers (e.g. alkenes) are added to each other one by one. The breaking of a double bond between carbon atoms in the monomer means that a bond can form with the next monomer.
- In a **condensation polymerisation reaction** a molecule of water is released as a product of the reaction. The water molecule is made up of atoms that have been lost from each of the monomers.
- The **chemical properties** of polymers (e.g. ability to withstand stress and melting point) are determined by the types of atoms in the polymer, and by the strength of the bonds between adjacent polymer chains. The stronger the bonds, the greater the strength of the polymer, and the higher its melting point.
- **Polyethene**, **polypropene**, **polyvinyl chloride**, **polyvinyl acetate** and **polystyrene** are all polymers formed through addition polymerisation.
- **Polyethylene terephthalate** and **polylactic acid** are polymers formed through condensation polymerisation.
- **Plastics** are a subgroup of organic polymers that can be molded. They can contain more than one polymer.
- It is not easy to **recycle** all plastics and so they create environmental problems.
- Some of these **environmental problems** include issues of waste disposal, air pollution and recycling.
- **Polylactic acid** is an example of a biodegradable polymer made from renewable resources.

**Exercise 4 – 33:**

1. Give **one word or phrase** for each of the following descriptions:
   a) The name of the homologous series to which 2-methylpropene belongs.
   b) The name of the functional group that gives alcohols their properties.
   c) The group of organic compounds that have acidic properties.
   d) The IUPAC name of the organic compound that is found in vinegar.
   e) The name of the organic compound that is found in alcoholic beverages.
2. When 1-propanol is oxidised by acidified potassium permanganate, the possible product formed is:
   - propane
   - propanoic acid
   - methyl propanol
   - propyl methanoate

   (IEB 2004)
3. What is the IUPAC name for the compound represented by the following structure?

```
      Cl   H    H
      |    |    |
  H — C —  C —  C — H
      |    |    |
      H    Cl   |
           H —  C — H
                |
                H
```

   - 1,2-dichlorobutane
   - 2,2-dichlorobutane
   - 1,2-dichloro-3-methylpropane
   - 1,1-dichloro-3-methylpropane

   (IEB 2003)

4. Give the structural representation and IUPAC name of all possible isomers for $C_6H_{14}$ (hint: there are 5)
5. Write balanced equations for the following reactions:
   a) Ethene reacts with bromine (use condensed structural representations)
   b) The complete combustion of ethyne gas (used molecular formula)
   c) Ethanoic acid ionises in water
6. The table gives the boiling point of ten organic compounds.

| | Compound | Molecular formula | Boiling Point (°C) |
|---|---|---|---|
| 1 | methane | $CH_4$ | $-162$ |
| 2 | ethane | $C_2H_6$ | $-89$ |
| 3 | propane | $C_3H_8$ | $-42$ |
| 4 | butane | $C_4H_{10}$ | 0 |
| 5 | pentane | $C_5H_{12}$ | 36 |
| 6 | methanol | $CH_4O$ | 64,7 |
| 7 | ethanol | $C_2H_6O$ | 78,4 |
| 8 | propan-1-ol | $C_3H_8O$ | 97 |
| 9 | propan-1,2-diol | $C_3H_8O_2$ | 188 |
| 10 | propan-1,2,3-triol | $C_3H_8O_3$ | 290 |

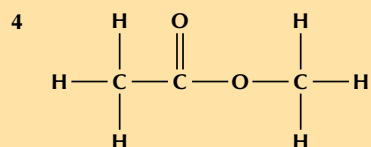
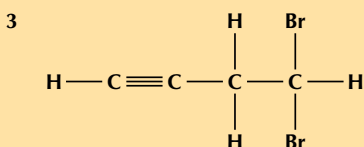
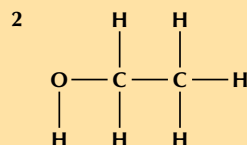
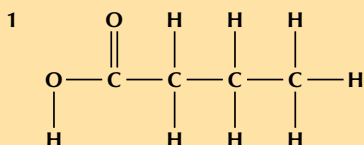
The following questions refer to the compounds shown in the above table.

   a) To which homologous series do the following compounds belong?
      i. Compounds 1 - 5
      ii. Compounds 6 - 10
   b) Which of the above compounds are gases at room temperature?
   c) What is the reason for the trend of increasing boiling points seen in compounds 1 to 5?
   d) Despite the fact that the length of the carbon chain in compounds 8,9 and 10 is the same, the boiling point of propan-1,2,3-triol is much higher than the boiling point of propan-1-ol. What is responsible for this large difference in boiling point?
   e) Give the IUPAC name and the structural representation of an isomer of butane.
   f) Which **one** of the compounds is used as a reactant in the preparation of the ester ethyl methanoate?
   g) Using structural representation, write an equation for the reaction which produces ethyl methanoate.

   (*IEB 2004*)

7. Refer to the numbered diagrams below and then answer the questions that follow.

```
1         O   H   H   H              2         H   H
          ‖   |   |   |                        |   |
     O —  C — C — C — C — H               O — C — C — H
     |        |   |   |                   |   |   |
     H        H   H   H                   H   H   H

3                 H   Br             4         H   O       H
                  |   |                        |   ‖       |
     H — C ≡ C — C — C — H               H — C — C — O — C — H
                  |   |                        |           |
                  H   Br                       H           H
```

   a) Which one of the above compounds is produced from the fermentation of starches and sugars in plant matter?

b) To which one of the following homologous series does compound 1 belong?

   i. esters    ii. alcohols    iii. aldehydes    iv. carboxylic acids

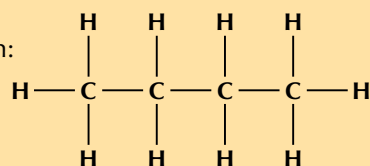
c) The correct IUPAC name for compound 3 is...

   i. 1,1-dibromobut-3-yne    ii. 4,4-dibromobut-1-yne
   iii. 2,4-dibromobut-1-yne    iv. 4,4-dibromoprop-1-yne

d) What is the correct IUPAC name for compound 4?

   i. propanoic acid    ii. ethyl methanoate
   iii. methyl ethanoate    iv. methyl propanoate

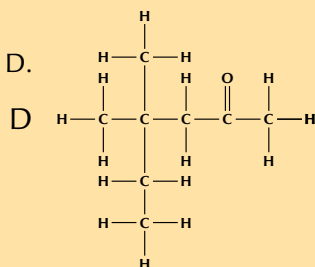
   *IEB 2005*

8. Answer the following questions:
   a) Explain the term homologous series.
   b) A mixture of ethanoic acid and methanol is warmed in the presence of concentrated sulfuric acid.
      i. Using structural representations, give an equation for the reaction which takes place.
      ii. What is the IUPAC name of the organic compound formed in this reaction?
   c) Consider the following hydrocarbon:

      i. Give the IUPAC name for this compound.
      ii. Give the balanced equation for the complete combustion of this compound in excess oxygen (use molecular formulae).

      (IEB Paper 2, 2003)

9. Consider the organic compounds labelled A to D.

   A. $CH_3CH_2CH_2CH_2CH_2CH_3$
   B. $C_6H_6$
   C. $CH_3 - Cl$

   D

   a) Write a balanced chemical equation for the preparation of compound C using an alkane as one of the reactants.
   b) Write down the IUPAC name for compound D.
   c) Write down the structural representation of an isomer of compound A that has only FOUR carbon atoms in the longest chain.
   d) Write down the structural representation of compound B.

10. Chlorine and ethane react to form chloroethane and hydrochloric acid.
    a) Write a balanced chemical equation for this reaction, using molecular formulae.
    b) Give the structural representation of chloroethane.
    c) What type of reaction has taken place in this example?

11. Petrol is in fact not pure $C_8H_{18}$ but a mixture of various *alkanes*. The *octane rating* of petrol refers to the percentage of the petrol which is $C_8H_{18}$. For example, 93 octane fuel contains 93% $C_8H_{18}$ and 7% other alkanes. The *isomer* of $C_8H_{18}$ referred to in the *octane rating* is in fact not octane but 2,2,4-trimethylpentane.
    a) Write a balanced equation for the chemical reaction which takes place when $C_8H_{18}$ burns in excess oxygen (complete combustion).
    b) Give the general formula of the *alkanes*.

c) Define the term *isomer*.

d) Use the information given in this question and your knowledge of naming organic compounds to deduce and draw the full structural formula for 2,2,4-trimethylpentane.(I.E.B.)

12. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

| | | | | | |
|---|---|---|---|---|---|
| 1a. 27QV | 1b. 27QW | 1c. 27QX | 1d. 27QY | 1e. 27QZ | 2. 27R2 |
| 3. 27R3 | 4. 27R4 | 5a. 27R5 | 5b. 27R6 | 5c. 27R7 | 6. 27R8 |
| 7. 27R9 | 8. 27RB | 9. 27RC | 10. 27RD | 11. 27RF | |

# CHAPTER

# *Work, energy and power*

## 5.1 Introduction ESCM9

We use the term 'work' in everyday conversation to mean many different things. We talk about going to work, doing homework, working in class. Physicists mean something very specific when they talk about work.

In Physics we use the term work to describe the process of transferring energy from object or system to another or converting energy from one form to another.

You will learn that work and energy are closely related to Newton's laws of motion. You shall see that the energy of an object is its capacity to do work and doing work is the process of transferring energy from one object or form to another by means of a force. In other words,

- an object with lots of energy can do lots of work.
- when object A transfers energy to object B, the energy of object A decreases by the same amount as the energy of object B increases, we say that object A does work on object B.

Lifting objects or throwing them requires that you do work on them. Even making an electrical current flow requires that something do work. Objects or systems must have energy to be able to do work on other objects or systems by transferring some of their energy.

**Key linked concepts**

- Units and unit conversions — Physical Sciences, Grade 10, Science skills
- Equations — Mathematics, Grade 10, Equations and inequalities
- Techniques of vector addition — Physical Sciences, Grade 10, Vectors and scalars
- Newton's laws — Physical Sciences, Grade 11, Forces
- Force diagrams — Physical Sciences, Grade 11, Forces

See video: 27RG at www.everythingscience.co.za

## 5.2 Work ESCMB

We cover different topics in different chapters in different grades but that doesn't mean that they are not related. In fact, it is very important to note that all of the different topics related to mechanics (forces, mechanical energy, momentum, rectilinear motion) actually form a **consistent** picture of the same physical system. There have been examples where we've shown the same results using two methods, for example determining speed or velocity using equations of motion or conservation of mechanical energy. Learning about work will help us tie everything we've learnt about previously together.

Work will allow us to connect energy transfer to forces, which we have already linked

to momentum and the equations of motion. When a force tends to act in or against the direction of motion of an object we say that the force is doing work on the object. Specifically, work is defined mathematically in terms of the force and the displacement of the object.

**DEFINITION:** *Work*

When a force acts in or against the direction of motion of an object, work is done on the object.

$$W = F\Delta x \cos\theta$$

This means that in order for work to be done, an object must have its position changed by an amount $\Delta\vec{x}$ while a force, $\vec{F}$, is acting on it such that there is some non-zero component of the force in the direction of the displacement.

Work is calculated as:

$$W = F\Delta x \cos\theta$$

Where:

- $W$ = work in joules (J)
- $F$ = magnitude of force for which we are calculating work in newtons (N)
- $\Delta x$ = magnitude of displacement in metres (m)
- $\theta$ = angle between the force and the direction of displacement

Note that:

- $F\cos\theta$ is the magnitude of the component of $\vec{F}$ in the direcion of $\Delta\vec{x}$. If $\theta > 90^o$ then the component is parallel to the direction of displacement but point in the opposite direction and the force is opposing the motion.
- We will deal with constant forces not forces that are continuously changing in this chapter. All of the principles we have covered are applicable when forces are not constant.

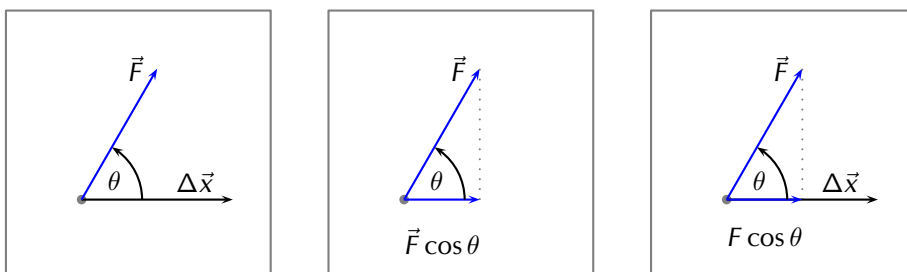
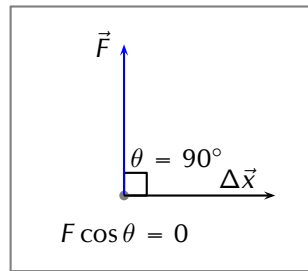
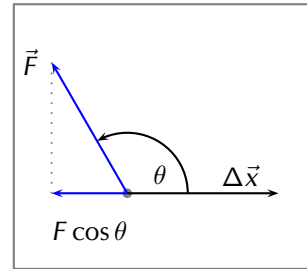



Figure 5.1: The force $\vec{F}$ causes the object to be displaced by $\Delta\vec{x}$ at angle $\theta$.

**Important:** $\cos\theta$ tells you the relative direciton of the force and the displacment which is important. If the component of the force along the direction of the displacement is opposite in direction to the displacement then the sign of the displacement vector and force vector will be different. This is regardless of which direction was chosen as a positive direction.

Let us look at some examples to understand this properly. In the images below the grey dot represents an object. A force, $\vec{F}$, acts on the object. The object moves through a displacement, $\Delta\vec{x}$. What is the sign of the work done in each case?

At $\theta = 90°$ the magnitude of the component of the force in the direction of the displacement is zero so **no work is done** as $\cos(90) = 0$.

At $\theta > 90°$ the magnitude of the component of the force along the line of the displacement is opposite in direction to the displacement so **negative work is done**, $\cos\theta < 0$.

It is very important to note that for work to be done there must be a component of the applied force in the direction of motion. Forces perpendicular to the direction of motion do no work.

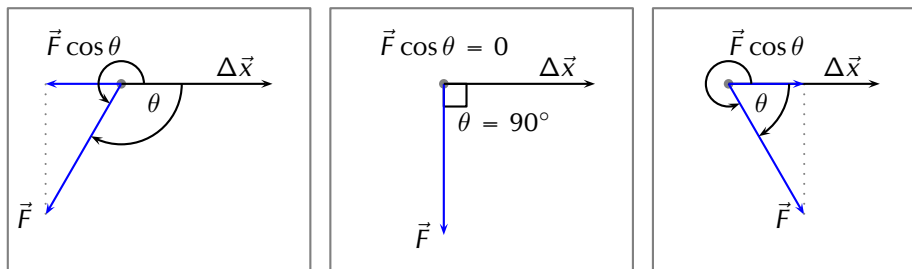



Figure 5.2: The force $\vec{F}$ causes the object to be displaced by $\Delta\vec{x}$ at angle $\theta$.

It is only the direction of the force on the object that matters and not the direction from the source of the force to the object. In Figure 5.3 both powerlifters are exerting an upwards force on the weights. On the left the weight is being pulled upwards and on the right it is being pushed upwards.

Figure 5.3: Left: A powerlifter deadlifts a weight. Right: A powerlifter benchpresses a weight.

Weight lifting is a good context in which to think about work because it helps to identify misconceptions introduced by everyday use of the term 'work'. In the two cases in Figure 5.3 everyone would describe moving the weights upwards as very hard work. From a physics perspective, as the powerlifters lift the weight they are exerting a force in the direction of the displacement so positive work is done on the weights.

Consider the strongman walking in Figure 5.4. He carries two very heavy sleds as far as he can in a competition. What work is the man doing on the sleds and why?

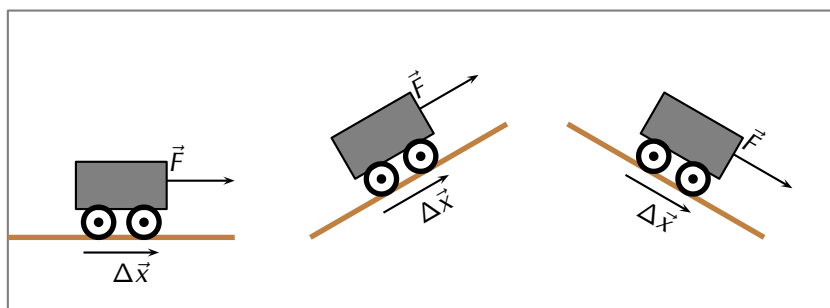
Most people would say he is working very hard because the sleds are heavy to carry but from a physics perspective he is doing no work on the sleds. The reason that he does no work is because the force he exerts is directly upwards to balance the force of gravity and the displacement is in the horizontal direction. Therefore there is no component of the force in the direction of displacement ($\theta = 90°$) and no work done.

His muscles do need to use their energy reserves to maintain the force to balance gravity. That does not result in energy transfer to the sleds.

Figure 5.4: A strongman carries heavy sleds as far as possible in a competition.

**Investigation: Is work done?**

Decide whether or not work is done in the following situations. Remember that for work to be done a force must be applied in the direction of motion and there must be a displacement. Identify which two objects are interacting, what the action-reaction pairs of forces are and why the force described is or isn't doing work.

1. Max pushes against a wall and becomes tired.
2. A book falls off a table and free falls to the ground.
3. A rocket accelerates through space.
4. A waiter holds a tray full of plates above his head with one arm and carries it straight across the room at constant speed.

For each of the above pictures, the force vector is acting in the same direction as the displacement vector. As a result, the angle $\theta = 0°$ because there is no difference in angle between the direction of applied force and the direction of displacement.

**TIP**

The everyday use of the word "work" differs from the physics use. In physics, only the component of the applied force that is parallel to the motion does work on an object. So, for example, a person holding up a heavy book does no work on the book.

The work done by a force can then be positive or negative. This sign tells us about the direction of the energy transfer. Work is a scalar so the sign should not be misinterpreted to mean that work is a vector. Work is defined as energy transfer, energy is a scalar quantity and the sign indicates whether energy was increased or decreased.

- If $\vec{F}_{applied}$ acts or has a component acting in the same direction as the motion, then positive work is being done. In this case the object on which the force is applied gains energy.
- If the direction of motion and $\vec{F}_{applied}$ are opposite, then negative work is being done. This means that energy is lost and the object exerting the force gains energy. For example, if you try to push a car uphill by applying a force up the slope and instead the car rolls down the hill you are doing negative work on the car. Alternatively, the car is doing positive work on you!

As with all physical quantities, work must have units. Following from the definition, work is measured in N·m. The name given to this combination of S.I. units is the joule (symbol J).

**Worked example 1: Calculating work on a car when speeding up.**

***QUESTION***

A car is travelling along a straight horizontal road. A force of 500 N is applied to the car in the direction that it is travelling, speeding it up. While it is speeding up is covers a distance of 20 m. Calculate the work done on the car.

***SOLUTION***

**Step 1: Analyse the question to determine what information is provided**

- The magnitude of the force applied is $F = 500$ N.
- The distance moved is $\Delta x = 20$ m.
- The applied force and distance moved are in the same direction. Therefore, the angle between the force and displacement is $\theta = 0°$.

These quantities are all in SI units, so no unit conversions are required.

**Step 2: Analyse the question to determine what is being asked**

- We are asked to find the work done on the car. We know from the definition that work done is $W = F\Delta x \cos\theta$.

**Step 3: Next we substitute the values and calculate the work done**

$$\begin{aligned} W &= F\Delta x \cos\theta \\ &= (500)(20)(\cos 0) \\ &= (500)(20)(1) \\ &= 10\,000 \text{ J} \end{aligned}$$

Remember that the answer must be *positive*, as the applied force and the displacement are in the same direction. In this case, the car gains kinetic energy.

**Worked example 2: Calculating work on the car while braking**

***QUESTION***

The same car now slows down when a force of 300 N is applied opposite to the direction of motion while it travels 25 m forward. Calculate the work done on the car.

***SOLUTION***

**Step 1: Analyse the question to determine what information is provided**

- The magnitude of the force applied is $F = 300$ N.
- The distance moved is $\Delta x = 25$ m.
- The applied force and distance moved are in the opposite direction. Therefore, the angle between the force and displacement is $\theta = 180°$.

These quantities are all in the correct units, so no unit conversions are required.

**Step 2: Analyse the question to determine what is being asked**

- We are asked to find the work done on the car. We know from the definition that work done is $W = F\Delta x \cos\theta$

**Step 3: Next we substitute the values and calculate the work done**

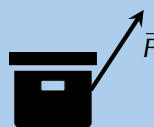
$$\begin{aligned} W &= F\Delta x \cos\theta \\ &= (300)(25)(\cos 180) \\ &= (300)(25)(-1) \\ &= -7500 \text{ J} \end{aligned}$$

Note that the answer must be *negative* as the applied force and the displacement are in opposite directions. This means that the energy is being lost by the car. This may be energy lost as heat to the environment. Energy conservation still holds, the energy has just been transferred to a larger system that contains the car.

What happens when the applied force and the motion are not parallel? By using the formula $W = F\Delta x \cos\theta$ , we are actually calculating the *component* of the applied force in the direction of motion. Note that the component of the force perpendicular to the direction of motion does no work.

**Worked example 3: Calculating work done on a box pulled at an angle.**

***QUESTION***

Calculate the work done on a box, if it is pulled 5 m along the ground by applying a force of $F = 20$ N at an angle of 60° to the horizontal.

***SOLUTION***

**Step 1: Analyse the question to determine what information is provided**

- The force applied is $F = 20$ N
- The distance moved is $\Delta x = 5$ m along the ground
- The angle between the applied force and the motion is $\theta = 60°$

These quantities are in the correct units so we do not need to perform any unit conversions.

**Step 2: Analyse the question to determine what is being asked**

- We are asked to find the work done on the box.

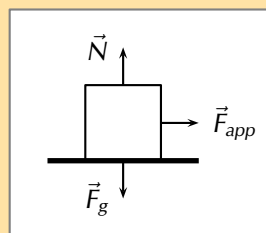
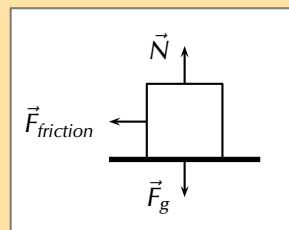
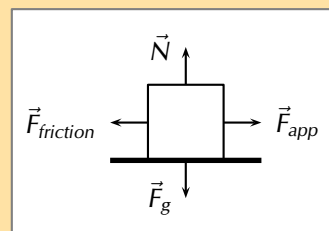
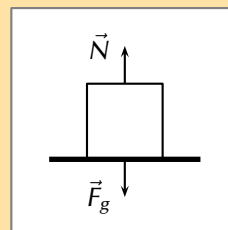
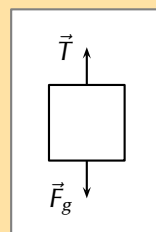
**Step 3: Substitute and calculate the work done**

Now we can calculate the work done on the box:

$$\begin{aligned} W &= F\Delta x \cos\theta \\ &= (20\ )(5\ )(\cos 60) \\ &= 50\ \text{J} \end{aligned}$$

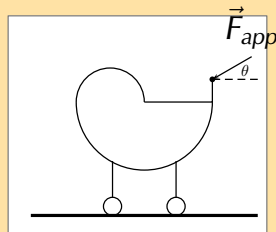
Note that the answer is positive as the component of the force parallel to the direction of motion is in the same direction as the motion.
The work done on the box is 50 J.

**Exercise 5 – 1: Work**

1. A 10 N force is applied to push a block across a frictionless surface for a displacement of 5,0 m to the right. The block has a weight $\vec{F}_g$ of 20 N. Determine the work done by the following forces: normal force, weight $\vec{F}_g$, applied force.

2. A 10 N frictional force slows a moving block to a stop after a displacement of 5,0 m to the right. The block has a weight of 20 N Determine the work done by the following forces: normal force, weight, frictional force.

3. A 10 N force is applied to push a block across a frictional surface at constant speed for a displacement of 5,0 m to the right. The block has a weight of 20 N and the frictional force is 10 N. Determine the work done by the following forces: normal force, weight, applied force and frictional force.

4. An object with a weight of 20 N is sliding at constant speed across a frictionless surface for a displacement of 5 m to the right. Determine if there is any work done.

5. An object with a weight of 20 N is pulled upward at constant speed by a 20 N force for a vertical displacement of 5 m. Determine if there is any work done.

6. Before beginning its descent, a roller coaster is always pulled up the first hill to a high initial height. Work is done on the roller coaster to achieve this initial height. A coaster designer is considering three different incline angles **of the hill** at which to drag the 2000 kg car train to the top of the 60 m high hill. In each case, the force applied to the car will be applied parallel to the hill. Her critical question is: which angle would require the least work? Analyse the data, determine the work done in each case, and answer this critical question.

| Angle of Incline | Applied Force | Distance | Work |
|---|---|---|---|
| 35° | $1{,}1 \times 10^4$ N | 100 m | |
| 45° | $1{,}3 \times 10^4$ N | 90 m | |
| 55° | $1{,}5 \times 10^4$ N | 80 m | |

7. A traveller carries a 150 N suitcase up four flights of stairs (a total height of 12 m) and then pushes it with a horizontal force of 60 N at a constant speed of 0,25 $\text{m}\cdot\text{s}^{-1}$ for a horizontal distance of 50 m on a frictionless surface. How much work does the traveller do on the suitcase during this entire trip?

8. A parent pushes down on a pram with a force of 50 N at an angle of 30° to the horizontal. The pram is moving on a frictionless surface. If the parent pushes the pram for a horizontal distance of 30 m, how work is done on the pram?

9. How much work is done by the force required to raise a 2000 N lift 5 floors vertically at a constant speed? The vertical distance between floors is 5 m high.
10. A student with a mass of 60 kg runs up three flights of stairs in 15 s, covering a vertical distance of 10 m. Determine the amount of work done by the student to elevate her body to this height.
11. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27RH 2. 27RJ 3. 27RK 4. 27RM 5. 27RN 6. 27RP
7. 27RQ 8. 27RR 9. 27RS 10. 27RT

## Net work ESCMC

We have only looked at a single force acting on an object. Sometimes more than one force acts at the same time (we dealt with this in Grade 11). We call the work done after taking all the forces into account the **net work done**. If there is only one force

acting then the work it does, if any, is the net work done. In this case there are two equivalent approaches we can adopt to finding the net work done on the object. We can:

- **Approach 1:** calculate the work done by **each force individually** and then sum them **taking the signs into account**. If one force does positive work and another does the same amount of work but it is negative then they cancel out.
- **Approach 2:** calculate the resultant force from all the forces acting and calculate the work done using the resultant force. This will be equivalent to Approach 1. If the resultant force parallel to the direction of motion is zero, no net work will be done.

Remember that work done tells you about the energy transfer to or from an object by means of a force. That is why we can have zero net work done even if multiple large forces are acting on an object. Forces that result in positive work increase the energy of the object, forces that result in negative work reduce the energy of an object. If as much energy is transferred to an object as is transferred away then the final result is that the object gains no energy overall.

**Worked example 4: Approach 1, calculating the net work on a car**

***QUESTION***

The same car is now accelerating forward, but friction is working against the motion of the car. A force of 300 N is applied forward on the car while it is travelling 20 m forward. A frictional force of 100 N acts to oppose the motion. Calculate the net work done on the car.

Only forces with a component in the plane of motion are shown on the diagram. No work is done by $F_g$ or $F_{Normal}$ as they act perpendicular to the direction of motion.

***SOLUTION***

**Step 1: Analyse the question to determine what information is provided**

- The force applied is $F_{applied} = 300$ N forwards.
- The force of friction is $F_{friction} = 100$ N opposite to the direction of motion.
- The distance moved is $\Delta x = 20$ m.
- The applied force and distance moved are in the same plane so we can calculate the work done by the applied forward force and the work done by the force of friction backwards.

These quantities are all in the correct units, so no unit conversions are required.

**Step 2: Analyse the question to determine what is being asked**

- We are asked to find the net work done on the car. We know from the definition that work done is $W = F\Delta x \cos\theta$

**Step 3: Next we calculate the work done by each force.**

$$
\begin{aligned}
W_{applied} &= F_{applied} \Delta x \cos\theta \\
&= (300)(20)(\cos 0) \\
&= (300)(20)(1) \\
&= 6000 \text{ J}
\end{aligned}
$$

$$
\begin{aligned}
W_{friction} &= F_{friction} \Delta x \cos\theta \\
&= (100)(20)(\cos 180) \\
&= (100)(20)(-1) \\
&= -2000 \text{ J}
\end{aligned}
$$

$$
\begin{aligned}
W_{net} &= W_{applied} + W_{friction} \\
&= (6000) + (-2000) \\
&= 4000 \text{ J}
\end{aligned}
$$

The answer shown in this worked example shows that although energy has been lost by the car to friction, the total work done on the car has resulted in a net energy gain. This can be seen by the positive answer.

As mentioned before, there is an alternative method to solving the same problem, which is to determine the net force acting on the car and to use this to calculate the work. This means that the vector forces acting in the plane of motion must be added to get the net force $\vec{F}_{net}$. The net force is then applied over the displacement to get the net work $W_{net}$.

**Worked example 5: Approach 2, calculating the net force**

***QUESTION***

The same car is now accelerating forward, but friction is working against the motion of the car. A force of 300 N is applied forward on the car while it is travelling 20 m forward. A frictional force of 100 N acts to oppose the motion. Calculate the net work done on the car.

***SOLUTION***

**Step 1: Analyse the question to determine what information is provided**

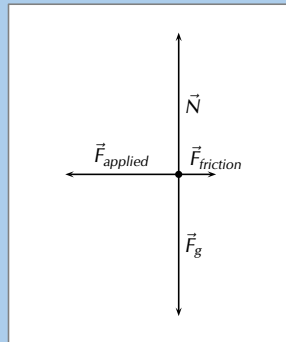
- The force applied is $\vec{F}_{applied} = 300$ N forwards.
- The force of friction is $\vec{F}_{friction} = 100$ N backwards.
- The distance moved is $\Delta x = 20$ m.
- The applied forces $\vec{F}_{applied} = 300$ N and the force of friction $\vec{F}_{friction} = 100$ N are in the same plane as the distance moved. Therefore, we can add the vectors. As vectors require direction, we will say that forward is positive and therefore backward is negative. Note, the force of friction is acting at $180^0$ i.e. backwards and so is acting in the opposite vector direction i.e. negative.

These quantities are all in the correct units, so no unit conversions are required.

**Step 2: Analyse the question to determine what is being asked**

- We are asked to find the net work done on the car. We know from the definition that work done is $W_{net} = F_{net} \Delta x \cos\theta$

**Step 3: We calculate the net force acting on the car, and we convert this into net work.**

First we draw the force diagram:

Let forwards (to the left in the picture) be positive. We know that the motion of the car is in the horizontal direction so we can neglect the force due to gravity, $\vec{F}_g$, and the normal force, $\vec{N}$. **Note:** if the car were on a slope we would need to calculate the component of gravity parallel to the slope.

$$\begin{aligned}\vec{F}_{net} &= \vec{F}_{applied} + \vec{F}_{friction} \\ &= (+300) + (-100) \\ \vec{F}_{net} &= 200 \text{ N forwards}\end{aligned}$$

$\vec{F}_{net}$ is pointing in the same direction as the displacement, therefore the angle between the force and displacement is $\theta = 0°$.

$$\begin{aligned}W_{net} &= F_{net}\Delta x \cos\theta \\ &= (200)(20)\cos(0) \\ &= 4000 \text{ J}\end{aligned}$$

**IMPORTANT!**

---

The two different approaches give the same result but it is very important to treat the signs correctly. The forces are vectors but work is a scalar so they shouldn't be interpreted in the same way.

---

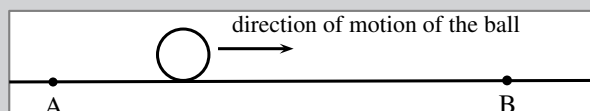
## 5.3 Work-energy theorem ESCMD

### Conservative and non-conservative forces ESCMF

In Grade 10, you saw that mechanical energy was conserved in the **absence** of non-conservative forces. It is important to know whether a force is an conservative force or an non-conservative force in the system, because this is related to whether the force can change an object's total mechanical energy when it does work on an object.

When the only forces doing work are conservative forces (for example, gravitational and spring forces), energy changes forms - from kinetic to potential (or vice versa); yet the total amount of mechanical energy ($E_K + E_P$) is conserved. For example, as an object falls in a gravitational field from a high elevation to a lower elevation, some of the object's potential energy is changed into kinetic energy. However, the sum of the kinetic and potential energies remain constant.

**Investigation: Non-conservative forces**

We can investigate the effect of non-conservative forces on an object's total mechanical energy by rolling a ball along the floor from point A to point B.

Find a nice smooth surface (e.g. a highly polished floor), mark off two positions, A and B, and roll the ball between them.

The total mechanical energy of the ball, at each point, is the sum of its kinetic energy ($E_k$) and gravitational potential energy ($E_p$):

$$\begin{aligned} E_{\text{total,A}} &= E_{k,\text{A}} + E_{p,\text{A}} \\ &= \frac{1}{2}mv_{\text{A}}^2 + mgh_{\text{A}} \\ &= \frac{1}{2}mv_{\text{A}}^2 + mg\,(0) \\ &= \frac{1}{2}mv_{\text{A}}^2 \end{aligned}$$

$$\begin{aligned} E_{\text{total,B}} &= E_{k\,\text{B}} + E_{p\,\text{B}} \\ &= \frac{1}{2}mv_{\text{B}}^2 + mgh_{\text{B}} \\ &= \frac{1}{2}mv_{\text{B}}^2 + mg\,(0) \\ &= \frac{1}{2}mv_{\text{B}}^2 \end{aligned}$$

In the absence of friction and other non-conservative forces, the ball should slide along the floor and its speed should be *the same* at positions A and B. Since there are no non-conservative forces acting on the ball, its total mechanical energy at points A and B are equal.

$$\begin{aligned} v_A &= v_{\text{B}} \\ \frac{1}{2}mv_{\text{A}}^2 &= \frac{1}{2}mv_B^2 \\ E_{\text{total,A}} &= E_{\text{total,B}} \end{aligned}$$

Now, let's investigate what happens when there is friction (an *non-conservative force*) acting on the ball.

Roll the ball along a rough surface or a carpeted floor. What happens to the speed of the ball at point A compared to point B?

If the surface you are rolling the ball along is very rough and provides a large non-conservative frictional force, then the ball should be moving much slower at point B than at point A.

Let's compare the total mechanical energy of the ball at points A and B:

$$\begin{aligned} E_{\text{total,A}} &= \text{EK}_{\text{A}} + \text{PE}_{\text{A}} \\ &= \frac{1}{2}mv_{\text{A}}^2 + mgh_{\text{A}} \\ &= \frac{1}{2}mv_{\text{A}}^2 + mg\,(0) \\ &= \frac{1}{2}mv_{\text{A}}^2 \end{aligned}$$

$$\begin{aligned} E_{\text{total,B}} &= \text{EK}_{\text{B}} + \text{PE}_{\text{B}} \\ &= \frac{1}{2}mv_{\text{B}}^2 + mgh_{\text{B}} \\ &= \frac{1}{2}mv_{\text{B}}^2 + mg\,(0) \\ &= \frac{1}{2}mv_{\text{B}}^2 \end{aligned}$$

However, in this case, $v_A \neq v_B$ and therefore $E_{\text{total,A}} \neq E_{\text{total,B}}$. Since

$$v_{\text{A}} > v_{\text{B}}$$
$$E_{\text{total,A}} > E_{\text{total,B}}$$

Therefore, the ball has lost mechanical energy as it moves across the carpet. However, although the ball has lost mechanical energy, energy in the larger system has still been conserved. In this case, the missing energy is the work done by the carpet through applying a frictional force on the ball. In this case the carpet is doing negative work on the ball.

When an non-conservative force (for example friction, air resistance, applied force) does work on an object, the total mechanical energy ($E_k + E_p$) of that object changes. If positive work is done, then the object will gain energy. If negative work is done, then the object will lose energy.

When a net **force does work** on an object, then there is **always a change in the kinetic energy** of the object. This is because the object experiences an acceleration and therefore a change in velocity.

This leads us to the work-energy theorem.

**DEFINITION:** *Work-energy theorem*

The work-energy theorem states that the work done on an object by the net force is equal to the change in its kinetic energy:

$$W_{net} = \Delta E_k = E_{k,f} - E_{k,i}$$

The work-energy theorem is another example of the conservation of energy which you saw in Grade 10.

### Worked example 6: Work-energy theorem

***QUESTION***

A 1 kg brick is dropped from a height of 10 m. Calculate the work that has been done on the brick between the moment it is released and the moment when it hits the ground. Assume that air resistance can be neglected.

***SOLUTION***

**Step 1: Determine what is given and what is required**

- Mass of the brick: $m = 1$ kg.
- Initial height of the brick: $h_i = 10$ m.
- Final height of the brick: $h_f = 0$ m.
- We are required to determine the work done on the brick as it hits the ground.

**Step 2: Determine how to approach the problem**

The brick is falling freely, so energy is conserved. We know that the work done is equal to the difference in kinetic energy. The brick has no kinetic energy at the moment it is dropped, because it is stationary. When the brick hits the ground, all the brick's potential energy is converted to kinetic energy.

**Step 3: Determine the brick's potential energy at $h_i$**

$$\begin{aligned} E_p &= m \cdot g \cdot h \\ &= (1)(9{,}8)(10) \\ &= 98 \text{ J} \end{aligned}$$

**Step 4: Determine the work done on the brick**

The brick had 98 J of potential energy when it was released and 0 J of kinetic energy. When the brick hit the ground, it had 0 J of potential energy and 98 J of kinetic energy. Therefore $E_{k,i} = 0$ J and $E_{k,f} = 98$ J.

From the work-energy theorem:

$$\begin{aligned} W_{net} &= \Delta E_k \\ &= E_{k,f} - E_{k,i} \\ &= 98 - 0 \\ &= 98 \text{ J} \end{aligned}$$

Hence, 98 J of work was done on the brick.

**Worked example 7: Work-energy theorem 2**

***QUESTION***

The driver of a 1000 kg car travelling at a speed of 16,7 $\text{m}\cdot\text{s}^{-1}$ applies the car's brakes when he sees a red light. The car's brakes provide a frictional force of 8000 N. Determine the stopping distance of the car.

***SOLUTION***

**Step 1: Determine what is given and what is required**

We are given:

- mass of the car: $m = 1000$ kg
- speed of the car: $v = 16{,}7\ \text{m}\cdot\text{s}^{-1}$
- frictional force of brakes: $\vec{F} = 8000$ N

We are required to determine the stopping distance of the car.

**TIP**
A force only does work on an object for the time that it is in contact with the object. For example, a person pushing a trolley does work on the trolley, but the road does no work on the tyres of a car if they turn without slipping (the force is not applied over any distance because a different piece of tyre touches the road every instant).

**Step 2: Determine how to approach the problem**

We apply the work-energy theorem. We know that all the car's kinetic energy is lost to friction. Therefore, the change in the car's kinetic energy is equal to the work done by the frictional force of the car's brakes.

Therefore, we first need to determine the car's kinetic energy at the moment of braking using: $E_k = \frac{1}{2}mv^2$

This energy is equal to the work done by the brakes. We have the force applied by the brakes, and we can use: $W = F\Delta x\cos\theta$

to determine the stopping distance.

**Step 3: Determine the kinetic energy of the car**

$$\begin{aligned} E_k &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(1000)(16{,}7)^2 \\ &= 139\,445 \text{ J} \end{aligned}$$

**Step 4: Determine the work done**

Assume the stopping distance is $\Delta x_0$. Since the direction of the applied force and the displacement are in opposite directions, $\theta = 180°$. Then the work done is:

$$\begin{aligned} W &= F\Delta x\cos\theta \\ &= (8000)(\Delta x_0)\cos(180) \\ &= (8000)(\Delta x_0)(-1) \\ &= (-8000)(\Delta x_0) \end{aligned}$$

**Step 5: Apply the work-enemy theorem**

The change in kinetic energy is equal to the work done.

$$\begin{aligned} \Delta E_k &= W_{net} \\ E_{k,f} - E_{k,i} &= (-8000)(\Delta x_0) \\ 0 - 139\,445 &= (-8000)(\Delta x_0) \\ \therefore \Delta x_0 &= \frac{139445}{8000} \\ &= 17{,}4 \text{ m} \end{aligned}$$

**Step 6: Write the final answer**

The car stops in 17,4 m.

**Worked example 8: Block on an inclined plane [credit: OpenStax College]**

***QUESTION***

A block of 2 kg is pulled up along a smooth incline of length 10 m and height 5 m by applying an non-conservative force. At the end of incline, the block is released from rest to slide down to the bottom. Find the

1. work done by the non-conservative force,

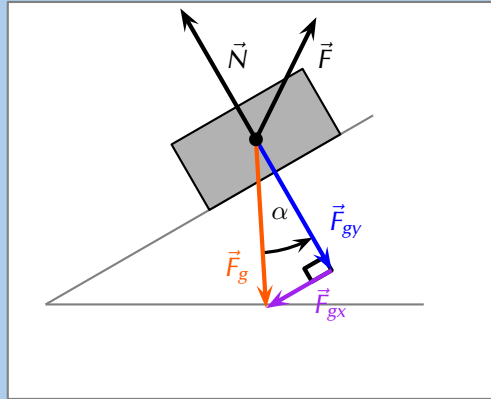
2. the kinetic energy of the block at the end of round trip, and
3. the speed at the end of the round trip.

***SOLUTION***

**Step 1: Analyse what is given and what is required**

There are three forces on the block while going up:

1. weight of the block, $\vec{F}_g = m\vec{g}$,
2. normal force, $\vec{N}$, applied by the block and
3. non-conservative force, $\vec{F}$.

On the other hand, there are only two forces while going down. The non-conservative force is absent in downward journey. The force diagram of the forces is shown here for upward motion of the block.

**Step 2: Work done by non-conservative force during round trip**

The work done by the non-conservative force we will call $W_F$.

We have not been given a magnitude or direction for $\vec{F}$, all we do know is that it must result in the block moving up the slope.

We have represented the non-conservative force on the force diagram with an arbitrary vector. $\vec{F}$ acts only during upward journey. Note that the block is simply released at the end of the upward journey. We need to find the work done by the non-conservative force only during the upward journey.

$$W_F = W_{F(up)} + W_{F(down)} = W_{F(up)} + 0 = W_{F(up)}$$

The kinetic energies in the beginning and at the end of the motion up the slope are zero.

We can conclude that sum of the work done by all three forces is equal to zero during the upward motion. The change in kinetic energy is zero which implies that the net work done is zero.

$$W_{net} = W_{F(up)} + W_{g(up)} + W_{N(up)}$$
$$0 = W_{F(up)} + W_{g(up)} + W_{N(up)}$$

If we know the work done by the other two forces (normal force and gravity), then we can calculate the work done by the non-conservative force, $F$, as required.

**Step 3: Work done by normal force during upward motion**

The block moves up the slope, the normal force is perpendicular to the slope and, therefore, perpendicular to the direction of motion. Forces that are perpendicular to

the direction of motion do no work.

$$\begin{aligned} 0 &= W_{F(up)} + W_{g(up)} + W_{N(up)} \\ 0 &= W_{F(up)} + W_{g(up)} + (0) \\ W_{F(up)} &= -W_{g(up)} \end{aligned}$$

Thus, we need to compute work done by the gravity in order to compute work by the non-conservative force.

**Step 4: Work done by gravity during upward motion**

The component of the force due to gravity that is perpendicular to the slope, $\vec{F}_{gy}$, will do no work so we only need to consider the component parallel to the slope, $\vec{F}_{gx}$.

For the upward motion $\vec{F}_{gx}$ is in the opposite direction to the motion, therefore the angle between them is $\theta = 180°$, which means $\cos\theta = -1$, so we expect to see negative work is done.

The magnitude of $\vec{F}_{gx}$ is $F_{gx} = mg\sin\alpha$. So the work done by gravity during the upward motion is :

$$\begin{aligned} W_{g(up)} &= F_{gx}\Delta x\cos\theta \\ &= mg\sin\alpha\cdot\Delta x\cos\theta \\ &= (2)(9{,}8)(\frac{5}{10})(10)\cos(180) \\ &= -98\text{ J} \end{aligned}$$

**IMPORTANT!**

---

Be careful not to be confused by which angle has been labelled $\alpha$ and which $\theta$. $\alpha$ is not the angle between the force and the direction of motion but the incline of the plane in this particular problem. It is important to understand which symbol represents which physical quantity in the equations you have learnt.

---

Hence, the work done by the non-conservative force during the round trip is:

$$\begin{aligned} W_F &= W_{F(up)} = -W_{g(up)} \\ &= -(-98) \\ &= 98\text{ J} \end{aligned}$$

**Step 5: Kinetic energy at the end of round trip**

The kinetic energy at the end of the upward motion was zero but it is not zero at the end of the entire downward motion.

We can use the work-energy theorem to analyse the whole motion:

$$\begin{aligned} W_{(round\ trip)} &= E_{k,f} - E_{k,i} \\ &= E_{k,f} - 0 \\ &= E_{k,f} \end{aligned}$$

To determine the net work done, $W_{(roundtrip)}$, we need to sum the work done by each force acting during the period. We have calculated the work done by $\vec{F}$ already and we know that there is no work done by the normal force.

The total work done during round trip by gravity is the sum of the work done during the upward motion (where the force is in the opposite direction to the motion) and the downward motion (where the force is in the same direction as the motion).

The distance over which the force acts is the same during the upward and downward motion and the magnitude of the force is the same. The only difference between the calculation for the work done during the upward and downward motion is the sign because of the change of direction of the motion. Therefore:

$$\begin{aligned} W_{g(round\ trip)} &= W_{g(up)} + W_{g(down)} \\ &= (mg \sin\alpha \cdot \Delta x \cos 180°) + (mg \sin\alpha \cdot \Delta x \cos 0°) \\ &= (-mg \sin\alpha \cdot \Delta x) + (mg \sin\alpha \cdot \Delta x) \\ &= 0 \text{ J} \end{aligned}$$

Hence, the total work done during round trip is:

$$\begin{aligned} W_{(round\ trip)} &= W_F + W_g + W_N \\ &= W_F + W_{g(up)} + W_{N(up)} \\ &= (98) + (0) + (0) \\ &= 98 \text{ J} \end{aligned}$$

We can now use this in the equation for the work-energy theorem:

$$\begin{aligned} W_{(round\ trip)} &= E_{k,f} \\ E_{k,f} &= 98 \text{ J} \end{aligned}$$

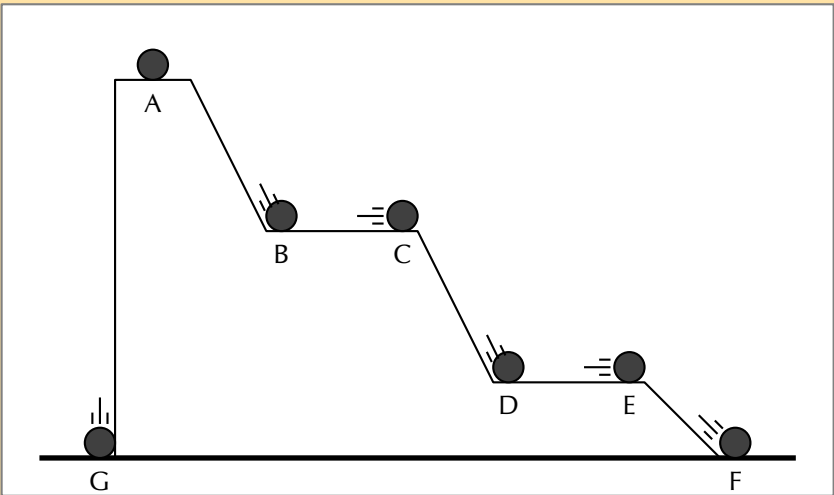
**Step 6: Speed of the block**

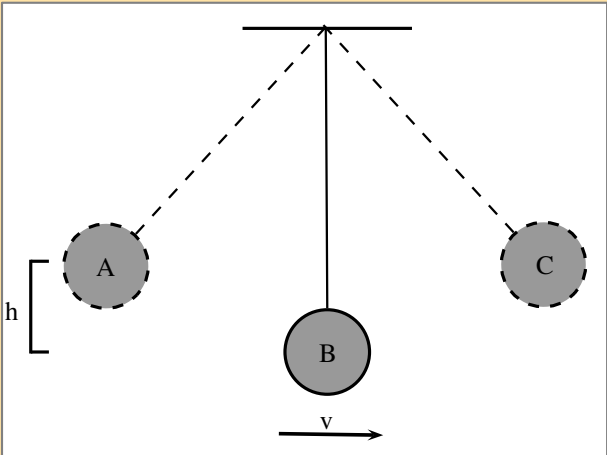
We know the kinetic energy of the block therefore we can determine its speed:

$$\begin{aligned} E_{k,f} &= \frac{1}{2}mv^2 \\ \frac{1}{2}mv^2 &= E_{k,f} \\ v &= \pm\sqrt{\frac{2}{m}E_{k,f}} \\ &= \pm\sqrt{\frac{2}{(2)}(98)} \\ &= \pm 9{,}89949493661 \\ &= 9{,}90 \text{ m·s}^{-1} \end{aligned}$$

Note that the total work done during the upward motion is zero as the block is stationary at the beginning and at the end of the motion up the incline. The positive work done by the non-conservative force is cancelled by the fact that exactly the same amount of negative work is done by gravity. The net work comes from the work done during the downward motion by gravity. Net work done results in a change in kinetic energy as per the work-energy theorem.

**Exercise 5 – 2: Energy**

1. Fill in the table with the missing information using the positions of the 1 kg ball in the diagram below combined with the work-energy theorem.

| position | *EK* | *PE* | v |
|---|---|---|---|
| A | | 50 J | |
| B | | 30 J | |
| C | | | |
| D | | 10 J | |
| E | | | |
| F | | | |
| G | | | |

2. A falling ball hits the ground at 10 $m \cdot s^{-1}$ in a vacuum. Would the speed of the ball be increased or decreased if air resistance were taken into account. Discuss using the work-energy theorem.
3. A pendulum with mass 300 g is attached to the ceiling. It is pulled up to point A which is a height h = 30 cm from the equilibrium position.

Calculate the speed of the pendulum when it reaches point B (the equilibrium point). Assume that there are no non-conservative forces acting on the pendulum.

4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27RV 2. 27RW 3. 27RX

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## 5.4 Conservation of energy ESCMG

There are two categories of forces we will consider, conservative and non-conservative.

**DEFINITION:** *Conservative force*

A conservative force is one for which work done by or against it depends only on the starting and ending points of a motion and not on the path taken.

A **conservative force** results in stored or **potential energy** and we can define a potential energy ($E_p$) for any conservative force.

Gravity is a conservative force and we studied gravitational potential energy in Grade 10. We now have all the concepts we need to actually deduce this ourselves. Let us consider pushing a ball up a number of different slopes.

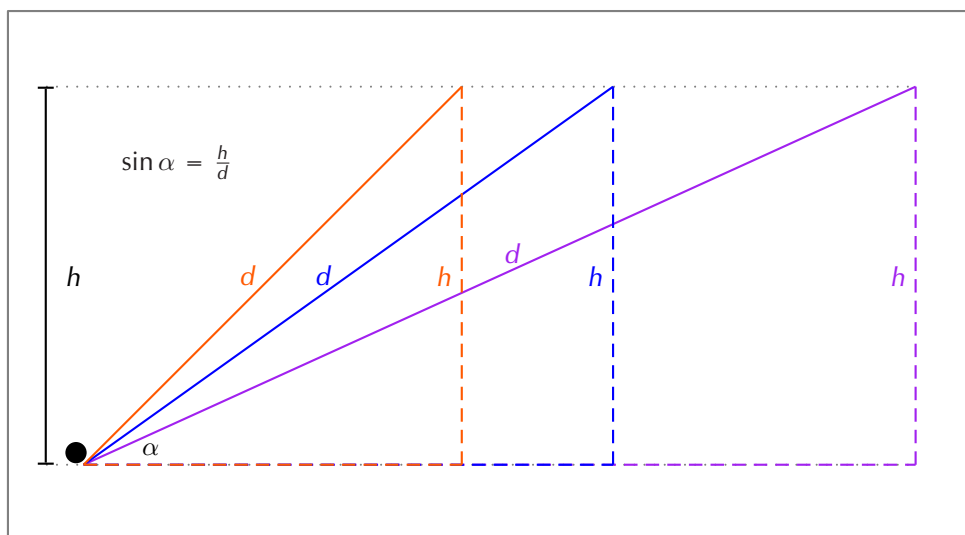
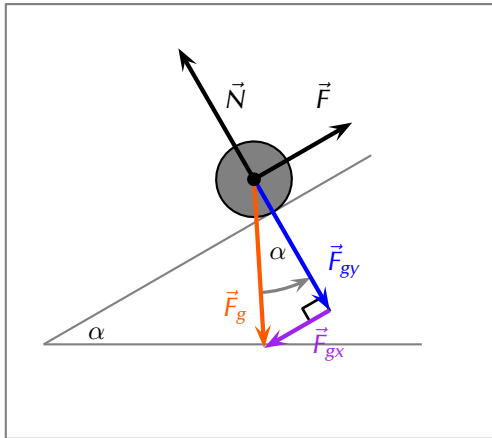



Figure 5.5: Three different slopes are shown, all rising to a height of $h$. The imaginary right-angled triangle is shown for each slope. $d$ is the length of the slope. $\alpha$ is the angle the slope makes with the horizontal.

The slope, of length $d$ is the hypotenuse of an imaginary right-angled triangle. The work done by gravity while pushing a ball of mass, $m$, up each of the slopes can be

calculated. We know that the component of the gravitational force parallel to the slope is $\vec{F}_{gx} = \vec{F}_g \sin\alpha$ down the slope.

The work done by gravity when the force $\vec{F}$ pushes the ball up the slope will be negative because the direction of the motion and $\vec{F}_g \sin\alpha$ are opposite.

$$
\begin{aligned}
W_g &= Fd\cos\theta \\
&= (\vec{F}_g \sin\alpha)d(-1) \\
&= -\vec{F}_g(\sin\alpha)d \\
&= -\vec{F}_g\left(\frac{\text{opposite}}{\text{hypotenuse}}\right)d \\
&= -\vec{F}_g\left(\frac{h}{d}\right)d \\
&= -\vec{F}_g h
\end{aligned}
$$

This final result is independent of the angle of the slope. This is because $\sin\alpha = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{h}{d}$ and so the distance cancels out. If the ball moves down the slope the only change is the sign, the work done by gravity still only depends on the change in height. This is why mechanical energy includes gravitational potential energy and is conserved. If an object goes up a distance $h$ gravity does negative work, if it moves back down $h$ gravity does positive work, but the absolute amount of work is the same so you 'get it back', no matter what path you take!

This means that the work done by gravity will be same for the ball moving up any of the slopes because the end position is at the same height. The different slopes do not end in exactly the same position in the picture. If we break each slope into two sections as show in Figure 5.6 then we have 3 different paths to precisely the same end-point. In this case the total work done by gravity along each path is the sum of the work done on each piece which is just related to the height. The total work done is related to the total height.

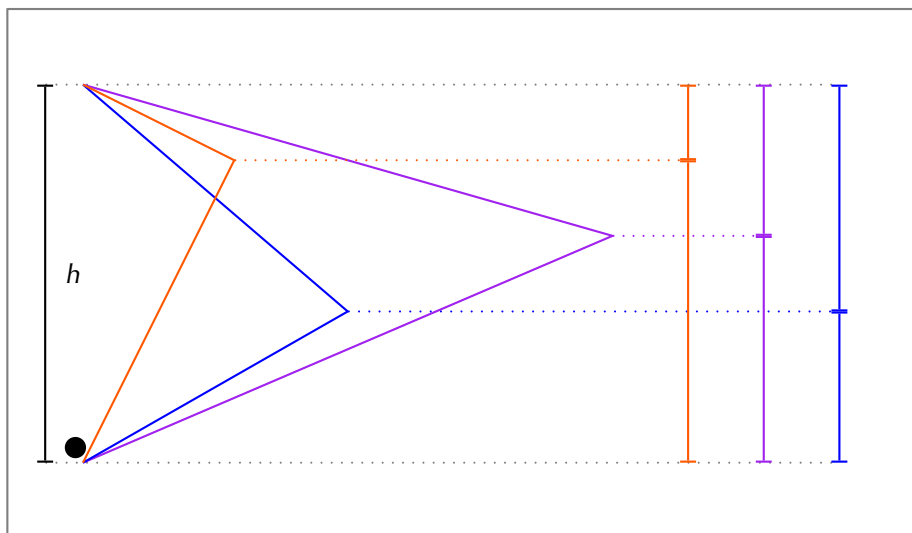



Figure 5.6: Three different paths that lead from the same start-point to the same-end point. Each path leads to the same overall change in height, $h$, and, therefore, the same work done by gravity.

There are other examples, when you wind up a toy, an egg timer, or an old-fashioned watch, you do work against its spring and store energy in it. (We treat these springs as ideal, in that we assume there is no friction and no production of thermal energy.) This stored energy is recoverable as work, and it is useful to think of it as potential energy contained in the spring.

The total work done by a conservative force results in a change in potential energy, $\Delta E_p$. If the conservative force does positive work then the change in potential energy is negative. Therefore:

$$W_{conservative} = -\Delta E_p$$

**DEFINITION:** *Non-conservative force*

A non-conservative force is one for which work done on the object depends on the path taken by the object.

**IMPORTANT!**

---

Non-conservative forces do not imply that total energy is not conserved. Total energy is always conserved. Non-conservative forces mean that mechanical energy isn't conserved in a particular system which implies that the energy has been transferred in a process that isn't reversible.

---

Friction is a good example of a non-conservative force because if removes energy from the system so the amount of mechanical energy is not conserved. Non-conservative forces can also do positive work thereby increasing the total mechanical energy of the system.

The energy transferred to overcome friction depends on the distance covered and is converted to thermal energy which can't be recovered by the system.

## Non-conservative forces and work-energy theorem ESCMH

We know that the net work done will be the sum of the work done by all of the individual forces:

$$\begin{aligned} F_{net} &= F_{conservative} + F_{non-conservative} \\ &\quad \text{(the work done by these forces yields)} \\ W_{net} &= W_{conservative} + W_{non-conservative} \\ &\quad \text{(using the work-energy theorem)} \\ \Delta E_k &= W_{conservative} + W_{non-conservative} \\ &\quad \text{(using } W_{conservative} = -\Delta PE\text{)} \\ \Delta E_k &= -\Delta E_p + W_{non-conservative} \\ W_{non-conservative} &= \Delta E_k + \Delta E_p \end{aligned}$$

When the non-conservative forces oppose the motion, the work done by the non-conservative forces is negative, causing a decrease in the mechanical energy of the system. When the non-conservative forces do positive work, energy is added to the system. If the sum of the non-conservative forces is zero then mechanical energy is conserved.

**Worked example 9: Sliding footballer [credit: OpenStax College Physics]**

***QUESTION***

Consider the situation shown where a football player slides to a stop on level ground. Using energy considerations, calculate the distance the 65,0 kg football player slides, given that his initial speed is 6,00 $m \cdot s^{-1}$ and the force of friction against him is a constant 450 N.

***SOLUTION***

**Step 1: Analyse the problem and determine what is given**

Friction stops the player by converting his kinetic energy into other forms, including thermal energy. In terms of the work-energy theorem, the work done by friction, which is negative, is added to the initial kinetic energy to reduce it to zero. The work done by friction is negative, because $F_f$ is in the opposite direction of the motion (that is, $\theta = 180°$, and so $\cos\theta = -1$). Thus $W_{non-conservative} = -F_f\Delta x$.

There is no change in potential energy.

**Step 2: Next we calculate the distance using the conservation of energy**

We begin with conservation of energy:

$$W_{non-conservative} = \Delta EK + \Delta PE$$

The equation expands to:

$$\begin{aligned}
W_{non-conservative} &= \Delta E_k + \Delta E_p \\
&= E_{k,f} - E_{k,i} + (0) \\
-F_f\Delta x &= E_{k,f} - E_{k,i} \\
-F_f\Delta x &= (0) - E_{k,i} \\
F_f\Delta x &= \frac{1}{2}mv_i^2 \\
\Delta x &= \frac{mv_i^2}{2F_f} \\
&= \frac{(65,0)(6,00)^2}{2(450)} \\
&= 2,60 \text{ m}
\end{aligned}$$

**Step 3: Quote the final answer**

The footballer comes to a stop after sliding for 2,60 m.

**Discussion**

The most important point of this example is that the amount of non-conservative work

equals the change in mechanical energy. For example, you must work harder to stop a truck, with its large mechanical energy, than to stop a mosquito.

**Worked example 10: Sliding up a slope [credit: OpenStax College Physics]**

***QUESTION***

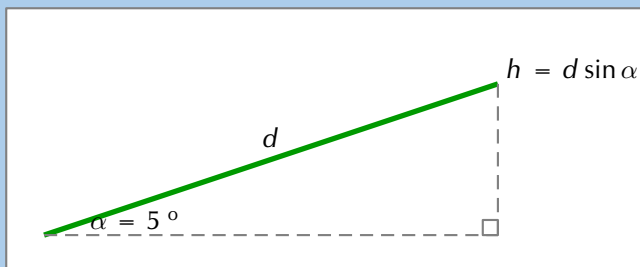
The same 65,0 kg footballer running at the same speed of 6,00 $m \cdot s^{-1}$ dives up the inclined embankment at the side of the field. The force of friction is still 450 N as it is the same surface, but the surface is inclined at 5 $^{o}$. How far does he slide now?

***SOLUTION***

**Step 1: Analyse the question**

Friction stops the player by converting his kinetic energy into other forms, including thermal energy, just in the previous worked example. The difference in this case is that the height of the player will change which means a non-zero change to gravitational potential energy.

The work done by friction is negative, because $F_f$ is in the opposite direction of the motion (that is, $\theta = 180^{o}$).

We sketch the situation showing that the footballer slides a distance $d$ up the slope.

In this case, the work done by the non-conservative friction force on the player reduces the mechanical energy he has from his kinetic energy at zero height, to the final mechanical energy he has by moving through distance $d$ to reach height $h$ along the incline. This is expressed by the equation:

$$W_{non-conservative} = \Delta E_k + \Delta E_p$$
$$W_{non-conservative} = E_{k,f} - E_{k,i} + E_{p,f} - E_{p,i}$$
$$W_{non-conservative} + E_{k,i} + E_{p,i} = E_{k,f} + E_{p,f}$$

We know that:

- the work done by friction is $W_{non-conservative} = -F_f d$,
- the initial potential energy is $E_{p,i} = mg(0) = 0$,
- the initial kinetic energy is $E_{k,i} = \frac{1}{2}mv_i^2$,
- the final kinetic energy is $E_{k,f} = 0$, and

- the final potential energy is $E_{p,f} = mgh = mgd\sin\theta$.

**Step 2: Solve for the distance**

$$\begin{aligned}
W_{non-conservative} + E_{k,i} + E_{p,i} &= E_{k,f} + E_{p,f} \\
(-F_f d) + \frac{1}{2}mv_i^2 + 0 &= 0 + mgd\sin\theta \\
(-F_f d) - mgd\sin\theta &= -\frac{1}{2}mv_i^2 \\
d(F_f + mg\sin\theta) &= \frac{1}{2}mv_i^2 \\
d &= \frac{\frac{1}{2}mv_i^2}{F_f + mg\sin\theta} \\
&= \frac{\frac{1}{2}(65,0)(6,00)^2}{450 + (65,0)(9,8)\sin(5,00)} \\
&= 2,31 \text{ m}
\end{aligned}$$

**Step 3: Quote the final answer**

The player slides for 2,31 m before stopping.

As might have been expected, the footballer slides a shorter distance by sliding uphill. Note that the problem could also have been solved in terms of the forces directly and the work energy theorem, instead of using the potential energy. This method would have required combining the normal force and force of gravity vectors, which no longer cancel each other because they point in different directions, and friction, to find the net force. You could then use the net force and the net work to find the distance $d$ that reduces the kinetic energy to zero. By applying conservation of energy and using the potential energy instead, we need only consider the gravitational potential energy, without combining and resolving force vectors. This simplifies the solution considerably.

**Exercise 5 – 3: Energy conservation**

1. A 60,0 kg skier with an initial speed of 12,0 m·s$^{-1}$ coasts up a 2,50 m-high rise as shown in the figure. Find her final speed at the top, given that the coefficient of friction between her skis and the snow is 0,0800. (Hint: Find the distance traveled up the incline assuming a straight-line path as shown in the figure.)

2. a) How high a hill can a car coast up (engine disengaged) if work done by friction is negligible and its initial speed is 110 km·h$^{-1}$?

   b) If, in actuality, a 750 kg car with an initial speed of 110 km·h$^{-1}$ is observed to coast up a hill to a height 22,0 m above its starting point, how much thermal energy was generated by friction?

c) What is the average force of friction if the hill has a slope 2,5 $^{o}$ above the horizontal?

3. A bullet traveling at 100 m/s just pierces a wooden plank of 5 m. What should be the speed (in m/s) of the bullet to pierce a wooden plank of same material, but having a thickness of 10m?
4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27RY  2. 27RZ  3. 27S2

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## 5.5 Power ESCMJ

Now that we understand the relationship between work and energy, we are ready to look at a quantity related the rate of energy transfer. For example, a mother pushing a trolley full of groceries can take 30 s or 60 s to push the trolley down an aisle. She does the same amount of work, but takes a different length of time. We use the idea of *power* to describe the rate at which work is done.

**DEFINITION:** *Power*

Power is defined as the rate at which work is done or the rate at which energy is transfered to or from a system. The mathematical definition for power is:
$P = \frac{W}{t}$

**FACT**
The unit watt is named after Scottish inventor and engineer James Watt (19 January 1736 - 19 August 1819) whose improvements to the steam engine were fundamental to the Industrial Revolution. A key feature of it was that it brought the engine out of the remote coal fields into factories.

**FACT**
Historically, the *horsepower* (symbol hp) was the unit used to describe the power delivered by a machine. One horsepower is equivalent to approximately 750 W. The horsepower was derived by James Watt to give an indication of the power of his steam engine in terms of the power of a horse, which was what most people used to for example, turn a mill wheel.

Power is easily derived from the definition of work. We know that: $W = F\Delta x \cos\theta$

Power is defined as the rate at which work is done. Therefore,

$$P = \frac{W}{t}$$
$$= \frac{F\Delta x \cos\theta}{t}$$

in the case where $F$ and $\Delta x$ are in the same direction

$$= \frac{F\Delta x}{t}$$
$$= F\frac{\Delta x}{t}$$
$$= Fv$$

**IMPORTANT!**

In the case where the force and the velocity are in opposite directions the power will be negative.

The unit of power is watt (symbol W).

## Worked example 11: Power calculation 1

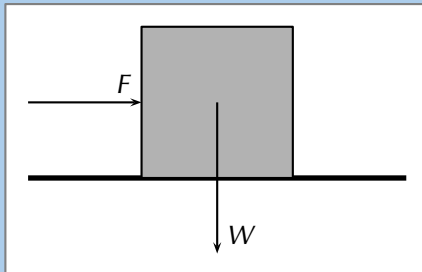
### *QUESTION*

Calculate the power required for a force of 10 N applied to move a 10 kg box at a speed of 1 m·s$^{-1}$ over a frictionless surface.

### *SOLUTION*

**Step 1: Determine what is given and what is required.**

- We are given the force, $F = 10$ N.
- We are given the speed, $v = 1\ \text{m} \cdot \text{s}^{-1}$.
- We are required to calculate the power required.

**Step 2: Draw a force diagram**

**Step 3: Determine how to approach the problem**

From the force diagram, we see that the weight of the box is acting at right angles to the direction of motion. The weight does not contribute to the work done and does not contribute to the power calculation. We can therefore calculate power from: $P = F \cdot v$.

**Step 4: Calculate the power required**

$$\begin{aligned} P &= F \cdot v \\ &= (10\ \text{N})\left(1\ \text{m} \cdot \text{s}^{-1}\right) \\ &= 10\ \text{W} \end{aligned}$$

**Step 5: Write the final answer**

10 W of power are required for a force of 10 N to move a 10 kg box at a speed of 1 m·s$^{-1}$ over a frictionless surface.

Machines are designed and built to do work on objects. All machines usually have a power rating. The power rating indicates the rate at which that machine can do work upon other objects.

A car engine is an example of a machine which is given a power rating. The power rating relates to how rapidly the car can accelerate. Suppose that a 50 kW engine could accelerate the car from 0 km·hr$^{-1}$ to 60 km·hr$^{-1}$ in 16 s. Then a car with four times the power rating (i.e. 200 kW) could do the same amount of work in a quarter of the time. That is, a 200 kW engine could accelerate the same car from 0 km·hr$^{-1}$ to 60 km·hr$^{-1}$ in 4 s.

## Worked example 12: Power calculation 2

### *QUESTION*

A forklift lifts a crate of mass 100 kg at a constant velocity to a height of 8 m over a time of 4 s. The forklift then holds the crate in place for 20 s. Calculate how much power the forklift exerts in lifting the crate? How much power does the forklift exert in holding the crate in place?

*SOLUTION*

**Step 1: Determine what is given and what is required**

We are given:

- mass of crate: $m = 100$ kg
- height that crate is raised: $h = 8$ m
- time taken to raise crate: $t_r = 4$ s
- time that crate is held in place: $t_s = 20$ s

We are required to calculate the power exerted.

**Step 2: Determine how to approach the problem**

We can use: $P = Fv = F\frac{\Delta x}{\Delta t}$

to calculate power. The force required to raise the crate is equal to the weight of the crate.

**Step 3: Calculate the power required to raise the crate**

$$\begin{aligned} P &= F\frac{\Delta x}{\Delta t} \\ &= m \cdot g\frac{\Delta x}{\Delta t} \\ &= \left(100 \text{ kg}\right)\left(9,8 \text{ m} \cdot \text{s}^{-2}\right)\frac{8 \text{ m}}{4 \text{ s}} \\ &= 1960 \text{ W} \end{aligned}$$

**Step 4: Calculate the power required to hold the crate in place**

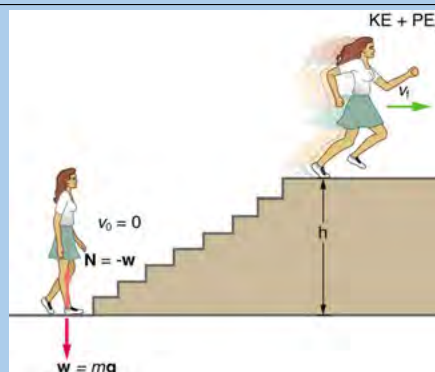
While the crate is being held in place, there is no displacement. This means there is no work done on the crate and therefore there is no power exerted.

**Step 5: Write the final answer**

1960 W of power is exerted to raise the crate and no power is exerted to hold the crate in place.

**Worked example 13: Stair climb**

*QUESTION*

What is the power output for a 60,0 kg woman who runs up a 3,00 m high flight of stairs in 3,50 s, starting from rest but having a final speed of 2,00 m·s$^{-1}$? Her power output depends on how fast she does this.

***SOLUTION***

**Step 1: Analyse the question**

The work going into mechanical energy is $W = E_k + E_p$. At the bottom of the stairs, we take both $E_k$ and the potential energy due to gravity, $E_{p,g}$, as initially zero; thus, $W = E_{k,f} + E_{p,g} = \frac{1}{2}mv_f^2 + mgh$, where $h$ is the vertical height of the stairs. Because all terms are given, we can calculate $W$ and then divide it by time to get power.

**Step 2: Calculate power**

Substituting the expression for $W$ into the definition of power given in the previous equation, $P = \frac{W}{t}$ yields:

$$\begin{aligned} P &= \frac{W}{t} \\ &= \frac{\frac{1}{2}mv_f^2 + mgh}{t} \\ &= \frac{\frac{1}{2}(60{,}0)(2{,}00)^2 + (60{,}0)(9{,}80)(3{,}00)}{3{,}50} \\ &= \frac{120 + 1764}{3{,}50} \\ &= 538{,}3 \text{ W} \end{aligned}$$

**Step 3: Quote the final answer**

The power generated is 538,0 W.

The woman does 1764 J of work to move up the stairs compared with only 120 J to increase her kinetic energy; thus, most of her power output is required for climbing rather than accelerating.

**Worked example 14: A borehole**

***QUESTION***

What is the power required to pump water from a borehole that has a depth $h$ = 15,0 m at a rate of 20,0 $\text{l}\cdot\text{s}^{-1}$?

***SOLUTION***

**Step 1: Analyse the question**

We know that we will have to do work on the water to overcome gravity to raise it a certain height. If we ignore any inefficiencies we can calculate the work, and power, required to raise the mass of water the appropriate height.

We know how much water is required in a single second. We can first determine the mass of water: 20,0 l $\times \frac{1 \text{ kg}}{1 \text{ l}} = 20{,}0$ kg.

The water will also have non-zero kinetic energy when it gets to the surface because it needs to be flowing. The pump needs to move 20,0 kg from the depth of the borehole

every second, we know the depth so we know the speed that the water needs to be moving is $v = \frac{h}{t} = \frac{15,0}{1} = 15,0\ \text{m}\cdot\text{s}^{-1}$.

**Step 2: Work done to raise the water**

We can use

$$\begin{aligned}
W_{non-conservative} &= \Delta E_k + \Delta E_p \\
&= E_{k,f} - E_{k,i} + E_{p,f} - E_{p,i} \\
&= \frac{1}{2}mv^2 - (0) + mgh - 0 \\
&= \frac{1}{2}(20)(15)^2 + (20)(9,8)(15) \\
&= 2,25 \times 10^3 + 2,94 \times 10^3 \\
&= 5,19 \times 10^3\ \text{J}
\end{aligned}$$

**Step 3: Calculate power**

$$\begin{aligned}
P &= \frac{W}{t} \\
&= \frac{5,19 \times 10^3}{1} \\
&= 5,19 \times 10^3\ \text{W}
\end{aligned}$$

**Step 4: Quote the final answer**

The minimum power required from the pump is $5,19 \times 10^3$ W.

**Experiment: Simple measurements of human power**

You can perform various physical activities, for example lifting measured weights or climbing a flight of stairs to estimate your output power, using a stop watch. Note: the human body is not very efficient in these activities, so your actual power will be much greater than estimated here.

**Exercise 5 – 4: Power**

1. [IEB 2005/11 HG] Which of the following is equivalent to the SI unit of power:
   a) V·A
   b) $\text{V}\cdot\text{A}^{-1}$
   c) $\text{kg}\cdot\text{m}\cdot\text{s}^{-1}$
   d) $\text{kg}\cdot\text{m}\cdot\text{s}^{-2}$
2. Two students, Bill and Bob, are in the weight lifting room of their local gym. Bill lifts the 50 kg barbell over his head 10 times in one minute while Bob lifts the 50 kg barbell over his head 10 times in 10 seconds. Who does the most work? Who delivers the most power? Explain your answers.
3. Jack and Jill ran up the hill. Jack is twice as massive as Jill; yet Jill ascended the same distance in half the time. Who did the most work? Who delivered the most power? Explain your answers.
4. When doing a chin-up, a physics student lifts her 40 kg body a distance of 0,25 m in 2 s. What is the power delivered by the student's biceps?
5. The unit of power that is used on a monthly electricity account is *kilowatt-hours* (symbol kWh). This is a unit of energy delivered by the flow of 1 kW of electricity for 1 hour. Show how many joules of energy you get when you buy 1 kWh of electricity.

6. An escalator is used to move 20 passengers every minute from the first floor of a shopping mall to the second. The second floor is located 5-meters above the first floor. The average passenger's mass is 70 kg. Determine the power requirement of the escalator in order to move this number of passengers in this amount of time.
7. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27S3 2. 27S4 3. 27S5 4. 27S7 5. 27S8 6. 27S9

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## 5.6 Chapter summary ESCMK

See presentation: 27SC at www.everythingscience.co.za

- **Kinetic energy**: $E_k = \frac{1}{2}mv^2$
- **Conservation of Energy**: Energy is never created nor destroyed, but is only transformed from one form to another.
- **Conservation of Mechanical Energy**: in the absence of non-conservative forces mechanical energy is conserved.
- When a force acting on an object has a component along the line of motion, work is done.
- Work is the process of transferring energy from object or system to another.
- Energy is the ability to do work.

| **Units** | | | | | |
|---|---|---|---|---|---|
| **Quantity** | **Symbol** | **Unit** | **S.I. Units** | | **Direction** |
| Velocity | $\vec{v}$ | — | $m{\cdot}s^{-1}$ | **or** $m{\cdot}s^{-1}$ | ✓ |
| Force | $\vec{F}$ | — | $kg{\cdot}m{\cdot}s^{-2}$ | **or** N | ✓ |
| Energy | E | J | $kg{\cdot}m^2{\cdot}s^{-2}$ | **or** $kg{\cdot}m^2{\cdot}s^{-2}$ | — |
| Work | W | J | $N{\cdot}m$ | **or** $kg{\cdot}m^2{\cdot}s^{-2}$ | — |
| Kinetic Energy | $E_K$ | J | $N{\cdot}m$ | **or** $kg{\cdot}m^2{\cdot}s^{-2}$ | — |
| Potential Energy | $E_P$ | J | $N{\cdot}m$ | **or** $kg{\cdot}m^2{\cdot}s^{-2}$ | — |
| Mechanical Energy | U | J | $N{\cdot}m$ | **or** $kg{\cdot}m^2{\cdot}s^{-2}$ | — |
| Power | P | W | $N{\cdot}m{\cdot}s^{-1}$ | **or** $kg{\cdot}m^2{\cdot}s^{-3}$ | — |

**Exercise 5 – 5:**

1. How much work does a person do in pushing a shopping trolley with a force of 200 N over a distance of 80 m in the direction of the force?
2. How much work does the force of gravity do in pulling a 20 kg box down a 45° frictionless inclined plane of length 18 m?

3. [IEB 2001/11 HG1] Of which one of the following quantities is $kg \cdot m^2 \cdot s^{-3}$ the base S.I. unit?

| a | Energy | c | Power |
|---|---|---|---|
| b | Force | d | Momentum |

4. [IEB 2003/11 HG1] A motor is used to raise a mass m through a vertical height h in time t. What is the power of the motor while doing this?

| a | $mght$ | c | $\frac{mgt}{h}$ |
|---|---|---|---|
| b | $\frac{mgh}{t}$ | d | $\frac{ht}{mg}$ |

5. [IEB 2002/11 HG1] An electric motor lifts a load of mass M vertically through a height h at a constant speed v. Which of the following expressions can be used to calculate the power transferred by the motor to the load while it is lifted at constant speed?

| a | $Mgh$ | c | $Mgv$ |
|---|---|---|---|
| b | $Mgh + \frac{1}{2}Mv^2$ | d | $Mgv + \frac{1}{2}\frac{Mv^3}{h}$ |

6. A set 193 kg containers need to be lifted onto higher floors during a building operation. The distance that they need to be raised is 7.5 m, at constant speed. The project manager has determined that in order to keep to budget and time this has to happen in as close to 5,0 s as possible. The power ratings for three motors are listed as 1,0 kW, 3,5 kW, and 5,5 kW. Which motor is best for the job?
7. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27SF 2. 27SG 3. 27SH 4. 27SJ 5. 27SK 6. 27SM

# CHAPTER

# *Doppler effect*

## 6.1 Introduction ESCMM

Have you noticed how the pitch of a police car or ambulance siren changes as it passes where you are standing, or how an approaching car or train sounds different to when it is tavelling away from you? If you haven't, try to do an experiment by paying extra careful attention the next time it happens to see if you can notice a difference in pitch. This doesn't apply to just vehicles and trains but anything that emits waves, be those sound waves or any other electromagnetic (EM) waves.

The effect actually occurs if you move towards or away from the source of the sound as well. This effect is known as the **Doppler effect** and will be studied in this chapter.

**Investigation: Creating the Doppler effect in class**

You can create the Doppler effect in class. One way of doing this is to get:

- string, and
- a tuning fork.

Tie the string to the base of the tuning fork. Strike the tuning fork to create a note and then hold the other end of the string and swing the tuning fork in circles in the air in a horizontal plane.

**WARNING!**

---

**The string needs to be very securely tied to the tuning fork to ensure that it does not come loose during the demonstration.**

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The class should be able to hear that the frequency heard when the tuning fork is moving is different to the frequency heard when it is stationary.

See video: 27SP at www.everythingscience.co.za

See video: 27SQ at www.everythingscience.co.za

See video: 27SR at www.everythingscience.co.za

**Key linked concepts**

- Units and unit conversions — Physical Sciences, Grade 10, Science skills
- Equations — Mathematics, Grade 10, Equations and inequalities
- Sound waves — Physical Sciences, Grade 10, Sound
- Electromagnetic radiation — Physical Sciences, Grade 10, Electromagnetic radiation

## 6.2 The Doppler effect with sound ESCMN

FACT

The Doppler effect is named after Johann Christian Andreas Doppler (29 November 1803 - 17 March 1853), an Austrian mathematician and physicist who first explained the phenomenon in 1842.

You, the person hearing the sounds, are called the *observer* or *listener* and the thing emitting the sound is called the *source*. As mentioned in the introduction, there are two situations which lead to the Doppler effect:

1. When the source moves relative to a stationary observer.
2. When the observer moves relative to a stationary source.

In points 1 and 2 above there is relative motion between the source and the observer. Both the source and the observer can be moving at the same time but we won't deal with that case in this chapter.

**DEFINITION:** *Doppler effect*

The Doppler effect is the change in the observed frequency of a wave when the source or the detector moves relative to the transmitting medium.

The Doppler effect occurs when a source of waves and/or observer move relative to each other, resulting in the observer measuring a different frequency of the waves than the frequency that the source is emitting. The medium that the waves are travelling through, the transmitting medium, is also stationary in the cases we will study.

The question that probably comes to mind is: *"How does the Doppler effect come about?"*. We can understand what is happening by thinking through the situation in detail.

### Case 1: Moving source, stationary observer ESCMP

Let us consider a source of sound waves with a constant frequency and amplitude. The sound waves can be represented as concentric circles where each circle represents a crest or peak as the wavefronts radiate away from the source. This is because the waves travel away from the source in all directions and the distance between consecutive crests or consecutive troughs in a wave is constant (the wavelength as we learnt in Grade 10). In this figure the crests are represented by by the black lines and the troughs by the orange lines.

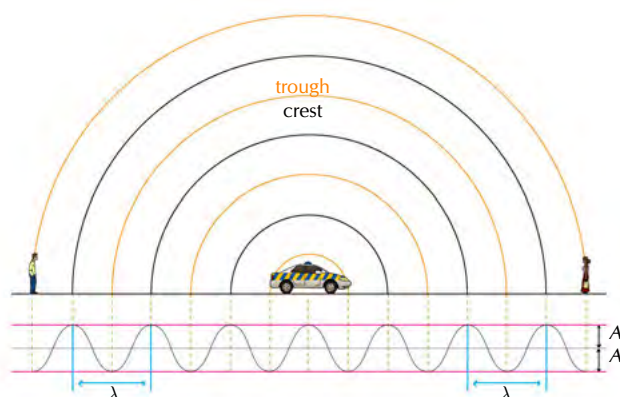
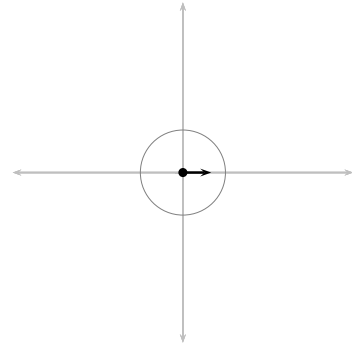
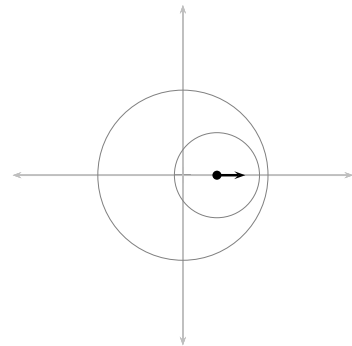
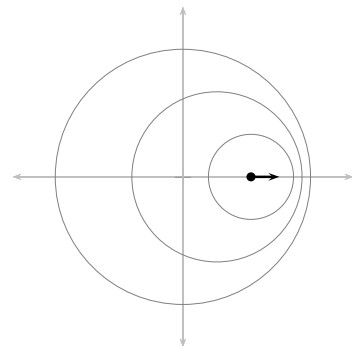



Figure 6.1: Stationary sound source as more wavefronts are emmitted.

The sound source is the police car in the middle and is stationary. For the Doppler effect to take place (manifest), the source must be moving *relative* to the observer.

Let's consider the following situation: The source (represented by the black dot) emits one wave (the black circles represent the crests of the sound wave) that moves away from the source at the same rate in all directions. The distance between the crests represents the wavelength ($\lambda$) of the sound. The closer together the crests, the higher the frequency (or pitch) of the sound according to $f = \frac{v}{\lambda}$, where $v$ (speed of sound) is constant.

As this crest moves away, the source also moves and then emits more crests. Now the two circles are not concentric any more, but on the one side they are closer together and on the other side they are further apart. This is shown in the next diagram.

If the source continues moving at the same speed in the same direction, then the distance between crests on the right of the source is constant. The distance between crests on the left is also constant. The distance between successive crests on the left is constant but larger than the distance between successive crests on the right.

When a car approaches you, the sound waves that reach you have a shorter wavelength and a higher frequency. You hear a sound with a higher pitch. When the car moves away from you, the sound waves that reach you have a longer wavelength and lower frequency. You hear a sound with a lower pitch.

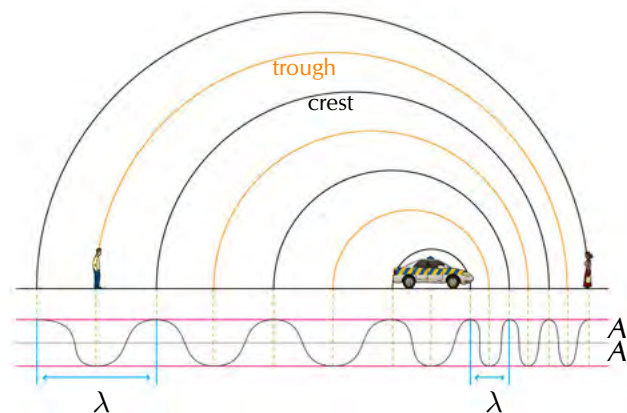



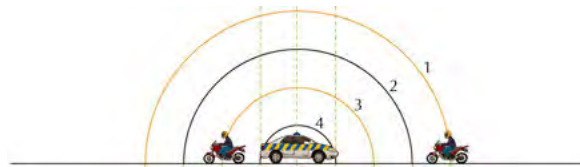
Figure 6.2: Moving sound source as more wavefronts are emmitted.

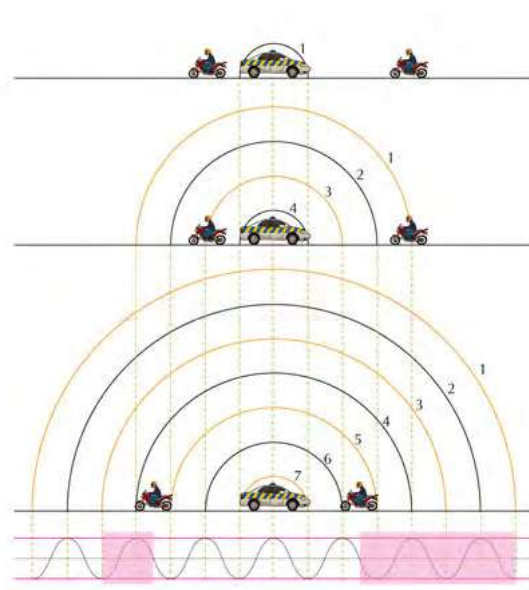
## Case 2: Moving observer, stationary source ESCMQ

Just as we did before, let us consider a source (a police car) of sound waves with a constant frequency and amplitude. There are two observers, one on the left that will move away from the source and one on the right that will move towards the source. We have three diagrams:

1. shows the overall situation with the siren starting at time $t_1$;
2. shows the situation at time $t_2$ when the observers are moving; and
3. shows the situation at $t_3$ after the observers have been moving for a time interval, $\Delta t = t_3 - t_2$.

The crests and troughs are numbered so you can see how they move further away and so that we can track which ones an observer has measured.

The observers can hear the sound waves emitted by the police car and they start to move (we ignore the time it takes them to accelerate).

The frequency of the wave that an observer measures is the number of complete waves cycles per unit time. By numbering the crests and troughs we can see which complete wave cycles have been measured by each of the observers in time, $\Delta t$. To find the frequency we divide the number of wave cycles by $\Delta t$.

In the time interval that passed, the observer moving towards the police car observed the crests and troughs numbered 1 through 5 (the portion of the wave is highlighted below). The observer moving away encountered a smaller portion of the wavefront, crest 3 and trough 4. The time interval for each of them is the same. To the observers this will mean that the frequency they measured is different.

The motion of the observer will alter the frequency of the measured sound from a stationary source:

- An observer moving **towards** the source measures a **higher** frequency.
- An observer moving **away from** the source measures a **lower** frequency.

It is important to note that we have only looked at the cases where the source and observer are moving directly towards or away from each other and these are the only cases we will consider.

**NOTE:**
We didn't actually need to analyse both cases. We could have used either explanation because of relative motion. The case of a stationary source with moving observer is the same as the case of the stationary observer and the moving source because the relative motion is the same. Do you agree? Discuss with your friends and try to convince yourselves that this is the case. Being able to explain work to each other will help you understand it better. If you don't understand it, you won't be able to explain it convincingly.
For a real conceptual test, discuss what you think will happen if the source and the observer are both moving, in the same direction and at the same speed.

The formula that provides the relationship between the frequency emitted by the source and the frequency measured by the listener is:

$$f_L = \left(\frac{v \pm v_L}{v \pm v_S}\right) f_S$$

- where $f_L$ is the frequency perceived by the observer (listener),
- $f_S$ is the frequency of the source,
- $v$ is the speed of the waves,
- $v_L$ the speed of the listener and
- $v_S$ the speed of the source.

Note: The signs show whether or not the relative motion of the source and observer is towards each other or away from each other:

| Source moves towards listener | $v_S$: negative |
|---|---|
| Source moves away from listener | $v_S$: positive |
| | |
| Listener moves towards source | $v_L$: positive |
| Listener moves away from source | $v_L$: negative |

We only deal with one of the source or observer moving in this chapter. To understand the sign choice you can think about the pictures of the motion. For the listener/observer we are using the numerator in the equation. A fraction gets larger when the numerator gets larger so if we expect the frequency to increase we expect addition in the numerator ($f_L = (\frac{v+v_L}{v})f_S$). If the numerator gets smaller the fraction gets smaller so if we expect the frequency to decrease then it is subtraction in the numerator ($f_L = (\frac{v-v_L}{v})f_S$).

For the denominator the reverse is true because of the fact that we divide by the denominator. The larger the denominator the smaller the fraction and vice versa. So if we expect the motion of the source to increase the frequency we expect subtraction in the denominator ($f_L = (\frac{v}{v-v_S})f_S$) and if we expect the frequency to decrease we expect addition in the denominator ($f_L = (\frac{v}{v+v_S})f_S$).

See video: 27SS at www.everythingscience.co.za

**Worked example 1: Ambulance siren**

***QUESTION***

The siren of an ambulance emits sound with a frequency of 700 Hz. You are standing on the pavement.

If the ambulance drives past you at a speed of 20 m·s$^{-1}$, what frequency will you hear, when

1. a) the ambulance is approaching you
2. b) the ambulance is driving away from you

Take the speed of sound in air to be 340 m·s$^{-1}$.

***SOLUTION***

**Step 1: Analyse the question**

The question explicitly asks what frequency you will hear when the source is moving at a certain speed. This tells you immediately that the question is related to the Doppler effect. The values given in the question are all in S.I. units so no conversions are required.

**Step 2: Determine how to approach the problem based on what is given**

We know that we are looking for the observed frequency with a moving source. The change in frequency can be calculated using:

$$f_L = \left(\frac{v \pm v_L}{v \pm v_S}\right) f_S$$

To correctly apply this we need to confirm that it is valid and determine what signs we need to use for the various speeds. You (the listener) are not moving but we have to consider two different cases, when the ambulance is moving towards you (a) and away from you (b). We have been told that if the source is moving towards the observer then we will use subtraction in the denominator and if it is moving away, addition. This means:

$$\begin{aligned} f_S &= 700 \text{ Hz} \\ v &= 340 \text{ m} \cdot \text{s}^{-1} \\ v_L &= 0 \text{ because you, the observer, are not moving} \\ v_S &= -20 \text{ m} \cdot \text{s}^{-1} \text{ for (a) and} \\ v_S &= +20 \text{ m} \cdot \text{s}^{-1} \text{ for (b)} \end{aligned}$$

**Step 3: Determine $f_L$ when ambulance is approaching**

$$\begin{aligned} f_L &= \left(\frac{v \pm v_L}{v \pm v_S}\right) f_S \\ f_L &= \left(\frac{340 + 0}{340 - 20}\right) (700) \\ &= 743{,}75 \text{ Hz} \end{aligned}$$

**Step 4: Determine $f_L$ when ambulance has passed**

$$\begin{aligned} f_L &= \left(\frac{v \pm v_L}{v \pm v_S}\right) f_S \\ f_L &= \left(\frac{340 + 0}{340 + 20}\right) (700) \\ &= 661{,}11 \text{ Hz} \end{aligned}$$

**Step 5: Quote the final answer**

When the ambulance is approaching you, you hear a frequency of 743,75 Hz and when it is going away you hear a frequency of 661,11 Hz

**Worked example 2: Moving observer**

***QUESTION***

What is the frequency heard by a person driving at 15 $\text{m}\cdot\text{s}^{-1}$ toward a factory whistle that is blowing at a frequency of 800 Hz. Assume that the speed of sound in air is 340 $\text{m}\cdot\text{s}^{-1}$.

***SOLUTION***

**Step 1: Analyse the question**

The question explicitly asks what frequency you will hear when the observer is moving at a certain speed. This tells you immediately that the question is related to the Doppler shift. The values given in the question are all in S.I. units so no conversions

are required.

**Step 2: Determine how to approach the problem based on what is given**

We can use:

$$f_L = \left(\frac{v \pm v_L}{v \pm v_S}\right) f_S$$

with:

$$\begin{aligned} v &= 340 \text{ m} \cdot \text{s}^{-1} \\ v_L &= +15 \text{ m} \cdot \text{s}^{-1} \\ v_S &= 0 \text{ m} \cdot \text{s}^{-1} \\ f_S &= 800 \text{ Hz} \\ f_L &= ? \end{aligned}$$

The listener is moving towards the source, so $v_L$ is positive and the source is stationary so $v_S = 0$.

**Step 3: Calculate the frequency**

$$\begin{aligned} f_L &= \left(\frac{v + v_L}{v + v_S}\right) f_S \\ &= \left(\frac{340 + 15}{340 + 0}\right)(800) \\ &= 835{,}29 \text{ Hz} \end{aligned}$$

**Step 4: Write the final answer**

The driver hears a frequency of 835,29 Hz.

**Worked example 3: Doppler effect [NSC 2011 Paper 1]**

***QUESTION***

A train approaches a station at a constant speed of 20 m·s$^{-1}$ with its whistle blowing at a frequency of 458 Hz. An observer, standing on the platform, hears a change in pitch as the train approaches him, passes him and moves away from him.

1. Name the phenomenon that explains the change in pitch heard by the observer. (1 mark)
2. Calculate the frequency of the sound that the observer hears while the train is approaching him. Use the speed of sound in air as 340 m·s$^{-1}$. (4 marks)
3. How will the observed frequency change as the train passes and moves away from the observer? Write down only INCREASES, DECREASES or REMAINS THE SAME. (1 mark)
4. How will the frequency observed by the train driver compare to that of the sound waves emitted by the whistle? Write down only GREATER THAN, EQUAL TO or LESS THAN. Give a reason for the answer. (2 marks)

**[TOTAL: 8 marks]**

***SOLUTION***

**Question 1:**

Doppler effect (1 mark)

**Question 2:**

$$\begin{aligned} f_L &= \frac{v \pm v_L}{v \pm v_S} f_S \\ \therefore f_L &= \frac{340 \pm 0}{340 - 20}(458) \\ &= 486{,}63 \text{ Hz} \end{aligned}$$

(4 marks)

**Question 3:**

Decreases (1 mark)

**Question 4**

Equal to, because ...

- the velocity of train driver relative to the whistle is zero. **OR**
- the train driver has same velocity as the whistle. **OR**
- there is no relative motion between source and observer.

(2 marks)

**[TOTAL: 11 marks]**

## Ultrasound and the Doppler effect ESCMR

Ultrasonic waves (ultrasound) are sound waves with a frequency greater than 20 000 Hz (the upper limit of human hearing). These waves can be used in medicine to determine the direction of blood flow. The device, called a Doppler flow meter, sends out sound waves. The sound waves can travel through skin and tissue and will be reflected by moving objects in the body (like blood). The reflected waves return to the flow meter where its frequency (received frequency) is compared to the transmitted frequency. Because of the Doppler effect, blood that is moving towards the flow meter will change the sound to a higher frequency and blood that is moving away from the flow meter will cause a lower frequency.

Ultrasound can be used to determine whether blood is flowing in the right direction in the circulation system of unborn babies, or identify areas in the body where blood flow is restricted due to narrow veins. The use of ultrasound equipment in medicine is called sonography or ultrasonography.

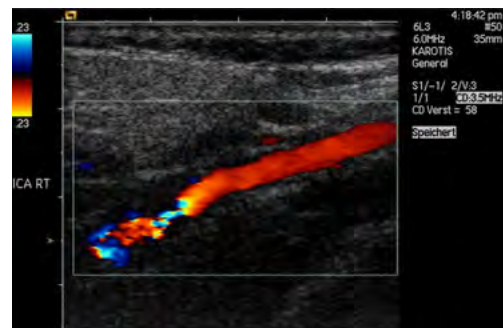



Figure 6.3: Colour Doppler imaging of cervicocephalic fibromuscular dysplasia

**Exercise 6 – 1: The Doppler effect with sound**

1. Suppose a train is approaching you as you stand on the platform at the station. As the train approaches the station, it slows down. All the while, the engineer is sounding the hooter at a constant frequency of 400 Hz. Describe the pitch of the hooter and the changes in pitch of the hooter that you hear as the train approaches you. Assume the speed of sound in air is 340 $m \cdot s^{-1}$.
2. Passengers on a train hear its whistle at a frequency of 740 Hz. Anja is standing next to the train tracks. What frequency does Anja hear as the train moves

directly toward her at a speed of 25 $m \cdot s^{-1}$? Assume the speed of sound in air is 340 $m \cdot s^{-1}$.

3. A small plane is taxiing directly away from you down a runway. The noise of the engine, as the pilot hears it, has a frequency 1,15 times the frequency that you hear. What is the speed of the plane? Assume the speed of sound in air is 340 $m \cdot s^{-1}$.
4. In places like Canada during winter temperatures can get as low as $-35$ °C . This affects the speed of sound in air and you can use the Doppler effect to determine what the speed of sound is. On a winter's day in Canada with a temperature of $-35$ °C , a source emits sound at a frequency of 1050 Hz and moves away from an observer at 25 $m \cdot s^{-1}$. The frequency that the observer measures is 971,41 Hz, what is the speed of sound?
5. Cecil approaches a source emitting sound with a frequency of 437,1 Hz.

    a) How fast does Cecil need to move to observe a frequency that is 20 percent higher?

    b) If he passes the source at this speed, what frequency will he measure when he is moving away?

    c) What is a practical means of achieving this speed?

    Assume the speed of sound in air is 340 $m \cdot s^{-1}$.
6. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27ST 2. 27SV 3. 27SW 4. 27SX 5. 27SY

 www.everythingscience.co.za 

## 6.3 The Doppler effect with light ESCMS

Light is a wave and earlier you learnt how you can study the properties of one wave and apply the same ideas to another wave. The same applies to sound and light. We know the Doppler effect is relevant in the context of sound waves when the source is moving. Therefore, in the context of light (EM waves), the frequency of observed light should be different to the emitted frequency when the source of the light is moving relative to the observer.

A frequency shift of light in the visible spectrum could result in a change of colour which could be observable with the naked eye. There will still be a frequency shift for frequencies of EM radiation we cannot see.

We can apply all the ideas that we learnt about the Doppler effect to light. When talking about light we use slightly different terminology to describe what happens. If you look at the colour spectrum (more details in Chapter 12) then you will see that blue light has a shorter wavelength than red light. Since for light, $c = f\lambda$, shorter wavelength equals higher frequency. Relative to the middle of the visible spectrum (approximately green light) longer wavelengths (or lower frequencies) are redder and shorter wavelengths (or higher frequencies) are bluer. So we call shifts towards longer wavelengths "redshifts" and shifts towards shorter wavelengths "blueshifts".

**TIP**
1. If the light source is moving away from the observer (positive velocity) then the observed frequency is lower and the observed wavelength is greater (redshifted).
2. If the source is moving towards the observer (negative velocity), the observed frequency is higher and the wavelength is shorter (blueshifted).

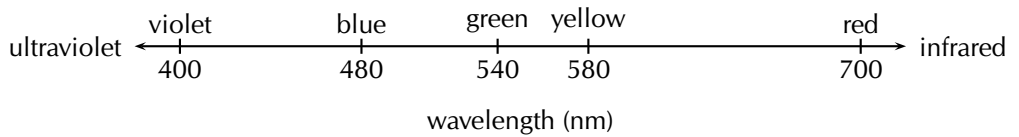



Figure 6.4: Blue light has a shorter wavelength than red light.

A shift in wavelength implies that there is also a shift in frequency. Longer wavelengths of light have lower frequencies and shorter wavelengths have higher frequencies. From the Doppler effect we know that when the source moves towards the observer any waves they emit that you measure are shifted to shorter wavelengths (blueshifted). If the source moves away from the observer, the shift is to longer wavelengths (redshifted).

## The expanding universe ESCMT

Stars emit light, which is why we can see them at night. Galaxies are huge collections of stars. An example is our own Galaxy, the Milky Way, of which our sun is only one of the billions of stars!

Using large telescopes like the Southern African Large Telescope (SALT) in the Karoo, astronomers can measure the light from distant galaxies. The spectrum of light can tell us what elements are in the stars in the galaxies because each element has unique energy levels and therefore emits or absorbs light at particular wavelengths. These characteristic wavelengths are called spectral lines because the lines show up as discrete frequencies in the spectrum of light from the star.

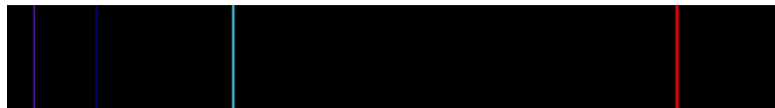



Figure 6.5: A subset of the spectral lines of hydrogen

If these lines are observed to be shifted from their usual wavelengths to shorter wavelengths, then the light from the galaxy is said to be *blueshifted*. If the spectral lines are shifted to longer wavelengths, then the light from the galaxy is said to be *redshifted*. If we think of the blueshift and redshift in Doppler effect terms, then a blueshifted galaxy would appear to be moving *towards* us (the observers) and a redshifted galaxy would appear to be moving *away* from us.

Edwin Hubble (20 November 1889 - 28 September 1953) measured the Doppler shift of a large sample of galaxies. He found that the light from distant galaxies is *redshifted* and he discovered that there is a proportionality relationship between the *redshift* and the *distance* to the galaxy. Galaxies that are further away always appear more redshifted than nearby galaxies. Remember that a redshift in Doppler terms means a velocity of the light source directed *away* from the observer. So why do all distant galaxies appear to be moving away from our Galaxy? None of them seem to be moving towards us.

:

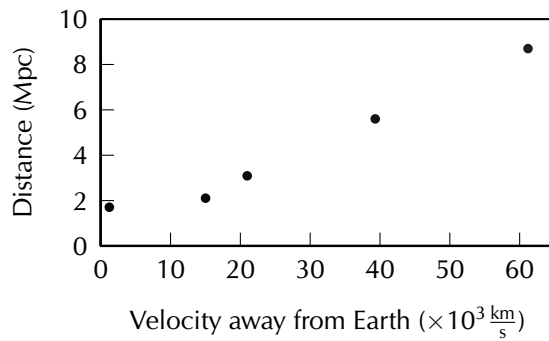



Figure 6.6: The distance to galaxies plotted against their speed away from us. The distance Mpc is a megaparsec which is very big, 1 Mpc = 3.3 million light years. A light year is the distance that light can travel in one year, 365 days × 24 hours × 60 minutes × 60 s × $3 \times 10^{8}\text{m}\cdot\text{s}^{-1}$ = $9.5 \times 10^{15}$ m.

**FACT**
Hubble Law is:

$$v = H_0 \times d$$

where latest value of $H_0$ is 67,15 $\text{km.s}^{-1}.\text{Mpc}^{-1}$ (rate of expansion of the Universe). Latest value from Planck mission, 2013.

**TIP**
Cool exercise that can be done with Sloan Digital Sky Survey data: http://skyserver.sdss3.org/dr8/en/proj/basic/universe_original/simple.asp

The reason is that the **universe is expanding!** Some of the galaxies will be moving in our direction but more slowly than the space between us and them is expanding. The expansion is so large that it is the primary effect that we observe. The primary reason the light is redshifted isn't actually because all of the Doppler effect, it is redshifted because the space is expanding, the waves are being stretched out. If the Doppler effect were a larger effect then some of the galaxies would still be blueshifted (just less than if space were not expanding).

**IMPORTANT!**

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You might think that this means we are at the centre of the universe. This isn't correct, the situation will look the same from every galaxy because space is expanding in all directions.

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There are two things you can do to help you visualise this a little better. One thing to try is to get a balloon and draw some dots on it with a marker. As you blow the balloon up all the dots get further away from all the other dots. The dots represent galaxies in a two-dimensional, expanding universe (the balloon surface). Another thing to imagine is baking raisin bread. As the bread rises, the distance between all the raisins gets larger. Every raisin thinks that all the other raisins are moving away from it.

In this picture the bottom vertex represents the beginning of time, the flat surface represents space. As you move up through the panels you are moving later in time and the expansion of the the flat surface shows the expansion of the universe. The galaxies shown on the surface get further away from each other just because of the expansion of space.

See video: 27SZ at www.everythingscience.co.za

## 6.4 Chapter summary ESCMV

See presentation: 27T2 at www.everythingscience.co.za

- The Doppler effect is a change in observed frequency due to the relative motion of a source and an observer.
- The following equation can be used to calculate the frequency of the wave according to the observer or listener:

$$f_L = \left( \frac{v + v_L}{v + v_S} \right) f_S$$

- If the direction of the wave from the listener to the source is chosen as positive, the velocities have the following signs:

| Source moves towards listener | $v_S$: negative |
|---|---|
| Source moves away from listener | $v_S$: positive |
| | |
| Listener moves towards source | $v_L$: positive |
| Listener moves away from source | $v_L$: negative |

- The Doppler effect can be observed in all types of waves, including ultrasound, light and radiowaves.
- Sonography makes use of ultrasound and the Doppler effect to determine the direction of blood flow.
- Light is emitted by stars. Due to the Doppler effect, the frequency of this light decreases and the stars appear redder than if they were stationary. This is called a red shift and means that the stars are moving away from the Earth. This is one of the reasons we can conclude that the Universe is expanding.

| **Physical Quantities** | | |
|---|---|---|
| **Quantity** | **Unit name** | **Unit symbol** |
| Frequency ($f$) | hertz | Hz |
| Speed ($v$) | metres per second | $m \cdot s^{-1}$ |

Table 6.1: Units used in **Doppler effect**.

**Exercise 6 – 2:**

1. Write a definition for each of the following terms.
   a) Doppler effect
   b) Redshift
   c) Ultrasound
2. The hooter of an approaching taxi has a frequency of 500 Hz. If the taxi is travelling at 30 $m \cdot s^{-1}$ and the speed of sound is 340 $m \cdot s^{-1}$, calculate the frequency of sound that you hear when
   a) the taxi is approaching you.

b) the taxi passed you and is driving away.

Draw a sketch of the observed frequency as a function of time.

3. A truck approaches you at an unknown speed. The sound of the truck's engine has a frequency of 210 Hz, however you hear a frequency of 220 Hz. The speed of sound is 340 $m \cdot s^{-1}$.

   a) Calculate the speed of the truck.

   b) How will the sound change as the truck passes you? Explain this phenomenon in terms of the wavelength and frequency of the sound.

4. **[Extension question]** A police car is driving towards a fleeing suspect at $\frac{v}{35} m \cdot s^{-1}$, where v is the speed of sound. The frequency of the police car's siren is 400 Hz. The suspect is running away at $\frac{v}{68}$. What frequency does the suspect hear?

5. Explain how the Doppler effect is used to determine the direction of flow of blood in veins.

6. An person in a car travelling at 22,2 $m \cdot s^{-1}$ approaches a source emitting sound waves with a frequency of 410 Hz. What is the frequency of the sound waves observed by the person? Assme the speed of sound in air is 340 $m \cdot s^{-1}$.

7. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27T3 2. 27T4 3. 27T5 4. 27T6 5. 27T7 6. 27T8

CHAPTER

# *Rate and Extent of Reaction*

## 7.1 Introduction ESCMW

A car slowly rusting away, a match burning, a tablet dissolving in water. All of these are chemical reactions and all of these take place at different rates. If you were to hold a race between these three reactions you would find that the match wins (it burns quickly), while the car rusting would lose (it may take years to rust).

In this chapter we will look at why reactions proceed at different rates (speeds) and how we can change the rate of the reaction.

Figure 7.1: A rusting car, a match burning and a tablet dissolving in water.

## 7.2 Rates of reaction and factors affecting rate ESCMX

Firstly, let's think about some different types of reactions and how quickly or slowly they occur.

**Exercise 7 – 1: Thinking about reaction rates**

1. Think about each of the following reactions (look at your Grade 11 textbook for a reminder on these processes):
   - corrosion (e.g. the rusting of iron)
   - weathering of rocks
   - photosynthesis
   - combustion

   a) For each of the reactions above, write a balanced chemical equation for the reaction that takes place.

   b) Rank these reactions in order from the fastest to the slowest.

   c) How did you decide which reaction was the fastest and which was the slowest?

   d) Think of some other examples of chemical reactions. How fast or slow is each of these reactions, compared with those listed earlier?

2. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27T9

This video is a simple demonstration of how a change in **surface area** can affect the average rate of a reaction.

See video: 27TB at www.everythingscience.co.za

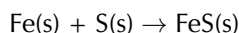
You can see how quickly the fuel burns when spread over the table. Think about how much more fuel would be needed to cook a meal if you had it spread over a large surface area rather than kept in a container with a small surface area.

**FACT**
In physics, speed is the scalar measurement that tells us how fast or slow an object is moving (position vs. time). For reactions the speed (or rate) of a reaction means how fast or slow the reaction is and indicates the amount of product formed and the amount of reactants used per unit time.

## What is a reaction rate? ESCMY

In a chemical reaction, the substances that are undergoing the reaction are called the **reactants**, while the substances that form as a result of the reaction are called the **products**. The **reaction rate** describes how quickly or slowly the reaction takes place. So how do we know whether a reaction is slow or fast? One way of knowing is to look either at how quickly the *reactants are used* during the reaction or at how quickly the *products form*. For example, iron and sulfur react according to the following equation:

$$Fe(s) + S(s) \rightarrow FeS(s)$$

+
FeS(s)

In this reaction, we can observe the speed of the reaction by measuring how long it takes before there is no iron or sulfur left in the reaction vessel. In other words, the reactants have been used. Alternatively, one could see how quickly the iron sulfide (the product) forms. Since iron sulfide looks very different from either of its reactants, this is easy to do.

In another example: $2Mg(s) + O_2(g) \rightarrow 2MgO(s)$

In this case, the reaction rate depends on the speed at which the reactants (oxygen gas and solid magnesium) are used, or the speed at which the product (magnesium oxide) is formed.

**DEFINITION:** *Reaction rate*

The average rate of a reaction describes how quickly *reactants are used* or how quickly *products are formed* during a chemical reaction.

The average rate of a reaction is expressed as the number of moles of reactant used, divided by the total reaction time, or as the number of moles of product formed, divided by the total reaction time.

Average reaction rate for:

- the use of a reactant $= \frac{\text{moles reactant used}}{\text{reaction time (s)}}$
- the formation of a product $= \frac{\text{moles product formed}}{\text{reaction time (s)}}$

Using the magnesium reaction shown earlier:

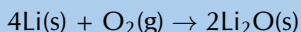
- Average reaction rate of Mg being used $= \frac{\text{moles Mg used}}{\text{reaction time (s)}}$
- Average reaction rate of $O_2$ being used $= \frac{\text{moles } O_2 \text{ used}}{\text{reaction time (s)}}$

- Average reaction rate of MgO being formed $= \frac{\text{moles MgO formed}}{\text{reaction time (s)}}$

**Worked example 1: Reaction rates**

***QUESTION***

The following reaction takes place:

$4Li(s) + O_2(g) \rightarrow 2Li_2O(s)$

After two minutes, 4 g of lithium has been used. Calculate the rate of the reaction.

***SOLUTION***

**Step 1: Calculate the number of moles of lithium that are used in the reaction**

$$n = \frac{m}{M} = \frac{4\text{ g}}{6{,}94\text{ g.mol}^{-1}} = 0{,}58\text{ mol}$$

**Step 2: Calculate the time (in seconds) for the reaction**

$t = 2\text{ minutes} = 2 \times 60\text{ s} = 120\text{ seconds}$

**Step 3: Calculate the rate of the reaction**

$$\text{Rate of reaction of Li used} = \frac{\text{moles of lithium used}}{\text{time}} = \frac{0{,}58\text{ mol}}{120\text{ s}} = 0{,}005\text{ mol.s}^{-1}$$

The rate of the reaction is $0{,}005\text{ mol.s}^{-1}$

**Exercise 7 – 2: Reaction rates**

1. A number of different reactions take place. The table below shows the number of moles of reactant that are used in a particular time for each reaction.

| Reaction | Reactants used (mol) | Time (s) | Reaction rate ($\text{mol.s}^{-1}$) |
|---|---|---|---|
| 1 | 2 | 30 | |
| 2 | 5 | 120 | |
| 3 | 1 | 90 | |
| 4 | 3,2 | 90 | |
| 5 | 5,9 | 30 | |

   a) Complete the table by calculating the average rate of each reaction.
   b) Which is the *fastest* reaction?
   c) Which is the *slowest* reaction?

2. Iron reacts with oxygen as shown in the balanced reaction:

   $2Fe(s) + O_2(g) \rightarrow 2FeO(s)$

   2 g of Fe and 0,57 g of $O_2$ are used during the reaction. 2,6 g of FeO is produced. The reaction takes 30 minutes to go to completion.

   Calculate the average rate of reaction for:
   a) the use of Fe.
   b) the use of $O_2$.
   c) the formation of FeO.

3. Two reactions occur simultaneously in separate reaction vessels. The reactions are as follows:

   $Mg(s) + Cl_2(g) \rightarrow MgCl_2(s)$

   $2Na(s) + Cl_2(g) \rightarrow 2NaCl(s)$

   After 1 minute, 2 g of $MgCl_2$ has been produced in the first reaction.

a) How many moles of $MgCl_2$ are produced after 1 minute?

b) Calculate the average rate of the reaction, using the amount of product that is produced.

c) Assuming that the second reaction also proceeds at the same rate, calculate:

  i. the number of moles of NaCl produced after 1 minute.

  ii. the minimum mass (in g) of sodium that is needed for this reaction to take place for 1 min.

4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27TC 2. 27TD 3. 27TF

 www.everythingscience.co.za 

## Reaction rates and collision theory ESCMZ

It should be clear now that the average rate of a reaction varies depending on a number of factors. But how can we explain why reactions take place at different speeds under different conditions? **Collision theory** is used to explain the rate of a reaction.

For a reaction to occur, the particles that are reacting must collide with one another. Only a fraction of all the collisions that take place actually cause a chemical change. These are called *successful* or *effective* collisions.

**DEFINITION:** *Collision theory*

Reactant particles must collide with the correct energy and orientation for the reactants to change into products.

Collision theory explains how chemical reactions occur and why reaction rates differ for different reactions. It states that for a reaction to occur the reactant particles must:

- collide
- have enough energy
- have the right orientation at the moment of impact

These *successful collisions* are necessary to break the existing bonds (in the reactants) and form new bonds (in the products).

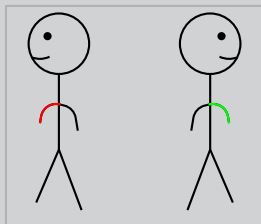
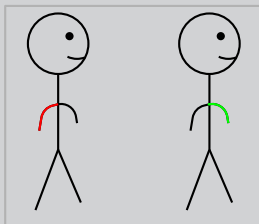
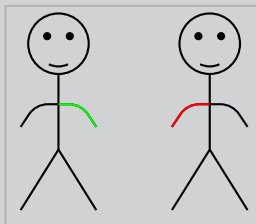
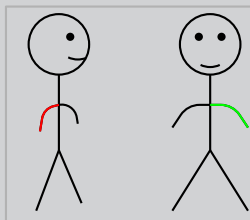
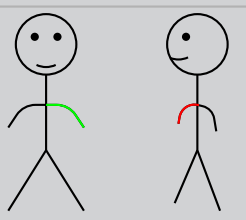
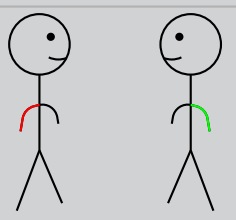
**Activity: Collision Theory**

**Aim:**

To determine the best way to approach your friend, in order to link your **right** arm with their **left** arm.

**Method:**

Try different ways of approaching your friend:

**FACT**
Oxalic acid is abundant in many plants. The leaves of the tea plant (*Camellia sinensis*) contain very high concentrations of oxalic acid relative to other plants. Oxalic acid also occurs in small amounts in foods such as parsley, chocolate, nuts and berries. Oxalic acid irritates the lining of the gut when it is eaten, and can be fatal in very large doses.

**Results:**
Determine how hard it is to link arms in each of these positions.

**Discussion:**
If you approach your friend from behind (facing their back) it is hard to link arms. Approaching from their left (sideways so that your right side is on their left), it is easy to link up.

**Conclusion:**
You should have found that each method had a different level of difficulty for linking arms. This is similar to how molecules (compounds) approach in a reaction. The different ways you approached your friend represent the different orientations of the molecules. The correct orientation makes successful collisions possible.

## Factors affecting reaction rates ESCN2

Several factors affect the average rate of a reaction. It is important to know these factors so that reaction rates can be controlled. This is particularly important when it comes to industrial reactions, where greater productivity leads to greater profits for companies. The following are some of the factors that affect the average rate of a reaction.

### Nature of reactants

Substances have different chemical properties and therefore react differently, and at different rates (e.g. the rusting of iron vs. the tarnishing of silver).

See video: 27TG at www.everythingscience.co.za

**Experiment: The nature of reactants**

**Aim:**

To determine the effect of the nature of reactants on the average rate of a reaction.

**Apparatus:**

You will need the following items for this experiment:

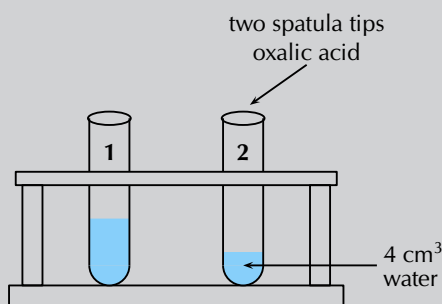
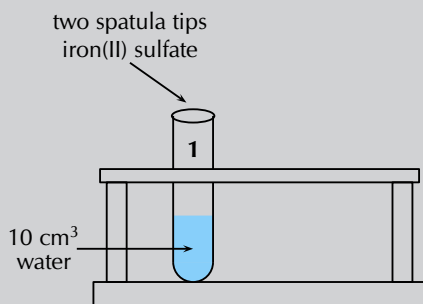
- Oxalic acid ($(COOH)_2$), iron(II) sulfate ($FeSO_4$), potassium permanganate ($KMnO_4$) and concentrated sulfuric acid ($H_2SO_4$)
- a spatula, two test tubes, a medicine dropper, a glass beaker and a glass rod.

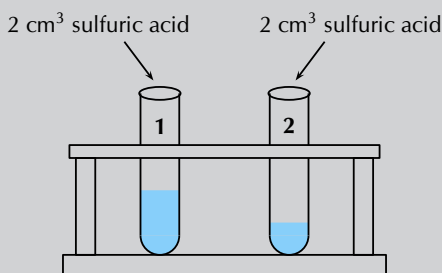
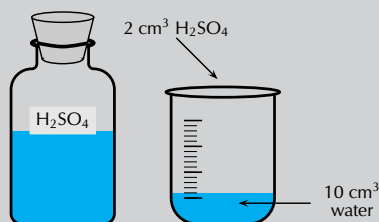
**Method:**

**WARNING!**

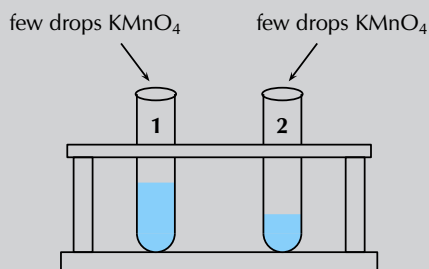
**Concentrated $H_2SO_4$ can cause serious burns. We suggest using gloves and safety glasses whenever you work with an acid. Remember to add the acid to the water and to avoid sniffing the acid. Handle all chemicals with care.**

1. Label one test tube **1**. Prepare an iron(II) sulfate solution in test tube 1 by dissolving two spatula tips of iron(II) sulfate in 10 $cm^3$ of water.

2. Label the other test tube **2**. Prepare a solution of oxalic acid in test tube 2 in the same way.

3. Prepare a separate solution of sulfuric acid by adding 2 $cm^3$ of the concentrated acid to 10 $cm^3$ of water. Remember always to add the **acid to the water**, and never the other way around.

4. Add 2 $cm^3$ of the sulfuric acid solution to the iron(II) sulfate and oxalic acid solutions respectively.

5. Using the medicine dropper, add a few drops of potassium permanganate to the two test tubes. Observe how quickly the potassium permanganate solution discolours in each solution.

few drops $KMnO_4$    few drops $KMnO_4$

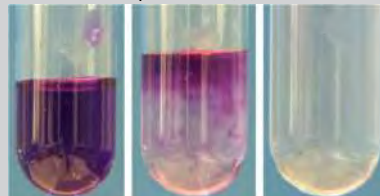
1   2

**Results:**

- You should have seen that the the potassium permanganate discolours in the oxalic acid solution much more slowly than in the iron(II) sulfate solution.

**FACT**
The $KMnO_4$ with oxalic acid and iron(II) sulfate pictures are screenshots from videos by katalofuromai and Aaron Huggard on Youtube.

$KMnO_4$ + oxalic acid

reaction takes a few minutes

$KMnO_4$ + iron(II) sulfate

reaction takes a few seconds

These reactions can be seen in the following videos:
See video: 27TH at www.everythingscience.co.za
See video: 27TJ at www.everythingscience.co.za

- It is the oxalate ions ($C_2O_4^{2-}$) and the $Fe^{2+}$ ions that cause the discolouration. It is clear that the $Fe^{2+}$ ions react much more quickly with the permanganate than the ($C_2O_4^{2-}$) ions. The reason for this is that there are no covalent bonds to be broken in the iron ions before the reaction can take place. In the case of the oxalate ions, covalent bonds between carbon and oxygen atoms must be broken first.

**Conclusions:**

Despite the fact that both these reactants (oxalic acid and iron(II) sulfate) are in aqueous solutions, with similar concentrations and at the same temperature, the reaction rates are very different. This is because the nature of the reactants can affect the average rate of a reaction.

The nature of the iron(II) sulfate in solution (iron ions, ready to react) is very different to the nature of oxalic acid in solution (oxalate ions with covalent bonds that must be broken). This results in significantly different reaction rates.

### Surface area (of solid reactants)

#### Experiment: Surface area and reaction rate

Marble ($CaCO_3$) reacts with hydrochloric acid (HCl) to form calcium chloride, water and carbon dioxide gas according to the following equation:
$CaCO_3(s) + 2HCl(\ell) \rightarrow CaCl_2(s) + H_2O(\ell) + CO_2(g)$

**Aim:**

To determine the effect of the surface area of reactants on the average rate of the reaction.

**Apparatus:**

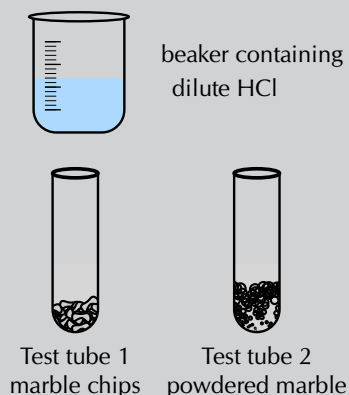
- 2 g marble chips, 2 g powdered marble, concentrated hydrochloric acid (HCl)
- one beaker, two test tubes.

**Method:**
**WARNING!**

---

**Concentrated HCl can cause serious burns. We suggest using gloves and safety glasses whenever you work with an acid. Remember to add the acid to the water and handle with care.**

---

1. Prepare a solution of hydrochloric acid in the beaker by adding 2 $cm^3$ of the concentrated acid to 20 $cm^3$ of water.
2. Place the marble chips into one test tube and the powdered marble into a separate test tube.
3. Add 10 $cm^3$ of the dilute hydrochloric acid to each of the test tubes and observe the rate at which carbon dioxide gas ($CO_2$) is produced (you should see bubbles of $CO_2$).

**Results:**

Note (write down) what you observe.

**Questions and discussion:**

- Which reaction proceeds faster?
- Can you explain this?

**Conclusion:**

The reaction with powdered marble is faster. The smaller the pieces of marble are (in this case the powdered form is smallest), the greater the surface area for the reaction to take place.

Only the molecules at the surface of the solid can react with the hydrochloric acid. The next layer of molecules can only react once the surface molecules have reacted. That is, the next layer of molecules becomes the surface.

The chips of marble are relatively large, so only a small percentage of the molecules are at the surface and can react initially. The powdered marble has much smaller solid pieces, so there are many more surface molecules exposed to the hydrochloric acid. The more molecules exposed on the surface (the greater the surface area) the faster the reaction will be.

For the same amount of mass, smaller pieces of solid react faster (shown in Figure 7.2).

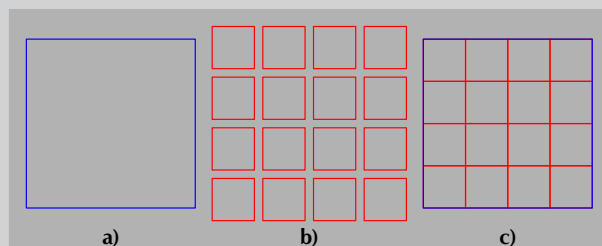



Figure 7.2: **a)** A large particle, **b)** small particles with the same volume as the large particle.

**c)** The surface area of large particles (shown in blue) is much smaller than that of small particles (shown in red).

See video: 27TK at www.everythingscience.co.za

Calcium carbonate reacts with hydrochloric acid according to the following reaction:

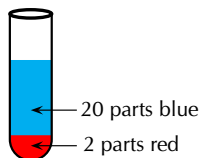
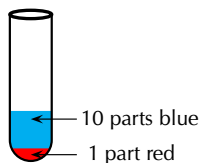
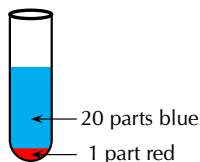
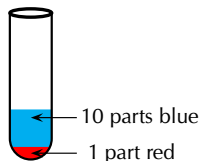
$CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + H_2O(\ell) + CO_2(g)$

Consider the solid calcium carbonate.

If we react 1 g of $CaCO_3$ we find that the reaction is faster if the $CaCO_3$ is powdered when compared with the $CaCO_3$ being large lumps.

**FACT**

Surface area, concentration and pressure all have the same effect on reaction rate (an increase leads to a faster reaction rate). This is because in each case an increase in the property leads to an increase in the number of collisions in that phase of matter.

**FACT**

**Explanation:**

The large lump of $CaCO_3$ has a small surface area relative to the same mass of powdered $CaCO_3$. This means that more particles of $CaCO_3$ will be in contact with HCl in the powdered $CaCO_3$ than in the lumps. As a result, there can be more *successful* collisions per unit time and the reaction of powdered $CaCO_3$ is faster.

**Increasing the surface area of the reactants increases the rate of the reaction.**

The following video shows the effect of surface area on the time an effervescent tablet takes to fully dissolve. The tablet is fully dissolved once the bubbles ($CO_2$ gas) stop forming.

See video: 27TM at www.everythingscience.co.za

### Concentration (of solutions)

As the concentration of the reactants increases, so does the reaction rate.

#### Experiment: Concentration and reaction rate

**Aim:**

To determine the effect of reactant concentration on reaction rate.

**Apparatus:**

- Concentrated hydrochloric acid (HCl), magnesium ribbon
- Two beakers, two test tubes and a measuring cylinder.

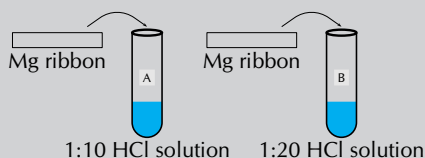
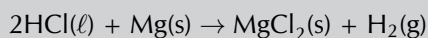
**Method:**

**WARNING!**

**Do not get hydrochloric acid (HCl) on your hands. We suggest you use gloves and safety glasses whenever handling acids and handle with care.**

1. When diluting a solution remember that if you want a 1:10 solution (1 part original solution in 10 parts water) measure 10 $cm^3$ of water in a measuring cylinder and pour it into a beaker, then add 1 $cm^3$ of the original solution to the beaker as well. 2 parts concentrated acid to 20 parts water will also be a 1:10 solution. Remember to always add the *acid* to the *water*, and not the other way around.
   - Prepare a solution of 1 part acid to 10 parts water (1:10). Label a test tube ***A*** and pour 10 $cm^3$ of this solution into the test tube.
   - Prepare a solution of 1 part acid to 20 parts water (1:20). Label a test tube ***B*** and pour 10 $cm^3$ of this solution into the test tube.
2. Take two pieces of magnesium ribbon of the **same length**. At the same time, put one piece of magnesium ribbon into test tube A and the other into test tube B, and pay close attention to what happens.
   **Make sure that the magnesium ribbon is long enough so that your hand is not close to the HCl.**

The equation for the reaction is:

$$2HCl(\ell) + Mg(s) \rightarrow MgCl_2(s) + H_2(g)$$

**Results:**

Write down what happened (what did you observe?) in each test tube.

**Questions and discussion:**

- Which of the two solutions is more concentrated, the 1:10 or 1:20 hydrochloric acid solution?
- In which of the test tubes is the reaction faster? Suggest a reason for this.
- How can you measure the average rate of this reaction?
- Name the gas that is produced?
- Why is it important that the same length of magnesium ribbon is used for each reaction?

**Conclusions:**

The 1:10 solution is more concentrated and therefore this reaction proceeds faster. The greater the concentration of the reactants, the faster the average rate of the reaction. The average rate of the reaction can be measured by the rate at which the magnesium ribbon disappears.

See video: 27TN at www.everythingscience.co.za

**Explanation:**

The greater concentration of the reactant means that there are more particles of reactant (HCl) per unit volume of solution. Therefore the chance that HCl particles will collide with the Mg particles will be higher for the solution with the greater concentration. The number of successful collisions per unit time will be higher and so the rate of the reaction will be faster.

See video: 27TP at www.everythingscience.co.za

**Project: Concentration and rate**

Design an experiment to determine the effect of concentration on rate using vinegar and baking soda.

**Hint:** mix water and vinegar to change concentration but keep the total volume constant.

**Pressure (of gaseous reactants)**

As the pressure of the reactants increase, so does the reaction rate.

The higher the pressure, the more particles of gas per unit volume. Therefore there are more collisions per unit time. The number of successful collisions per unit time will be higher and so the rate of the reaction will be faster.

See video: 27TQ at www.everythingscience.co.za

**Temperature**

If the temperature of the reaction increases, so does the average rate of the reaction.

**Experiment: Temperature and reaction rate**

**Aim:**

To determine the effect of temperature on reaction rate.

**Apparatus:**

- Two effervescent tablets (e.g. Cal-C-Vita)
- An ice-bath, two test tubes
- Two balloons, two rubber bands

**Method:**

1. Half fill two large test tubes with water. Label them *A* and *B*.
2. Break two effervescent tablets in two or three pieces and place them in the two balloons. Fit one of these balloons tightly to test tube A and one to test tube B, being careful not to drop the contents into the water. You can stand the test tube in a beaker to help you do this.
3. Place *only* test tube A into an ice-bath and leave to equilibrate (come to the same temperature). Approximately 10 minutes should be enough.
4. At the same time lift the balloons on test tubes A and B so that the tablets go into the water. **Do not** shake either test tube.

$CO_2$(g) is released during this reaction.

Observe how quickly the balloons increase in size and write down your observations (which increases in size faster).

**Results:**

Note (write down) your observations.

**Questions and discussion:**

- Which balloon expanded faster?
- Suggest a reason for the difference in rates.

**Conclusions:**

The balloon on test tube B will expand faster. This is because the higher temperature (room temperature rather than an ice bath) leads to an increase in the average rate of $CO_2$ gas production.

The video below shows how much pressure can build up when $CO_2$(g) is released during the reaction of an effervescent tablet with water.

See video: 27TR at www.everythingscience.co.za

The higher the temperature, the greater the average kinetic energy of the particles, which means that the particles are moving faster. Therefore:

- particles moving faster means more collisions per unit time (collision theory)
- particles with higher kinetic energy are also more likely to react on colliding

as they have enough energy for the reaction to occur (see Section 7.4 on the mechanism of reaction).

See video: 27TS at www.everythingscience.co.za

### Catalyst

Adding a catalyst increases the reaction rate by lowering the energy required for a successful reaction to take place. A catalyst speeds up a reaction and is released at the end of the reaction, completely unchanged.

## Experiment: Catalysts and reaction rate

**Aim:**
Hydrogen peroxide decomposes slowly over time into water and oxygen. The aim of this experiment is to determine the effect a catalyst has on the reaction rate.

**Apparatus:**

- 3% hydrogen peroxide ($H_2O_2$), manganese dioxide ($MnO_2$) powder, yeast powder
- two beakers or large measuring cylinders

**Method:**

**WARNING!**

**Be careful when handling $H_2O_2$ as it can burn you. We recommend wearing gloves and safety glasses.**

1. Pour 30 $cm^3$ $H_2O_2$ into two seperate containers.
2. Add a spatula tip of yeast to one container.
3. Time how long it takes for the bubbles to stop.
4. Repeat with $MnO_2$ in the second container.
5. Compare the effect of the two catalysts.

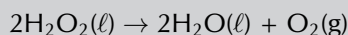
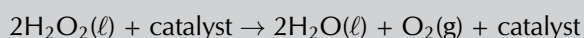



Figure 7.3: $H_2O_2$ before the addition of $MnO_2$ (left) and after the addition of $MnO_2$ (right).

The balanced equation for this reaction is:

$2H_2O_2(\ell) \rightarrow 2H_2O(\ell) + O_2(g)$

This can also be written:

$2H_2O_2(\ell) + \text{catalyst} \rightarrow 2H_2O(\ell) + O_2(g) + \text{catalyst}$

**Results:**

- Which chemical compounds are acting as catalysts in these reactions?
- What causes the bubbles that form in the reaction?

**Conclusions:**
The bubbles that form are oxygen gas formed through the decomposition of hydrogen peroxide. This would happen over time without the presence of the catalyst. The manganese dioxide speeds up the reaction significantly. The yeast speeds up the reaction, but not as much as the manganese dioxide.

See video: 27TT at www.everythingscience.co.za

**Experiment: Catalysts and reaction rate**

**Aim:**

To determine the effect of a catalyst on the average rate of a reaction

**Apparatus:**

- Zinc granules, 0,1 $mol.dm^{-3}$ hydrochloric acid, copper pieces
- One test tube, a glass beaker, tongs

**Method:**

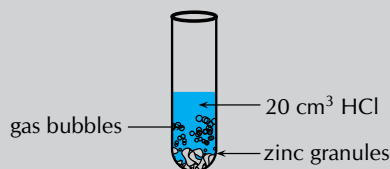
**WARNING!**

---

**Do not get hydrochloric acid (HCl) on your hands. We suggest you use gloves and safety glasses whenever handling acids. Be especially careful when removing the copper pieces from the test tube.**

---

1. Place a few of the zinc granules in the test tube, using tongs.
2. Measure the mass of a few pieces of copper and, using tongs, keep them separate from the rest of the copper.
3. Add 20 $cm^3$ of HCl to the test tube. You will see that a gas is released. Take note of how quickly or slowly this gas is released (use a stopwatch or your cellphone to time this). Write a balanced chemical equation for the chemical reaction that takes place.

4. Now add the copper pieces to the same test tube. What happens to the rate at which the gas is produced?
5. Carefully remove the copper pieces from the test tube (use tongs), rinse them in water and alcohol and then weigh them again. Has the mass of the copper changed since the start of the experiment?

**Results:**

During the reaction, the gas that is released is hydrogen. The rate at which the hydrogen is produced *increases* when the copper pieces (the catalyst) are added. The mass of the copper does not change during the reaction.

**Conclusions:**

The copper acts as a *catalyst* during the reaction. It speeds up the average rate of the reaction, but is not changed itself in any way.

We will return to catalysts in more detail once we have explored the mechanism of reactions later in this chapter.

**Experiment: Temperature, concentration and reaction rate**

**Aim:**

To determine the effect of temperature and concentration on the average reaction rate of the iodine clock experiment. This experiment is best done in groups.

**Apparatus:**

- Potassium iodide (KI), soluble starch, sodium thiosulfate solution ($Na_2S_2O_3$),

dilute (around 0,2 $mol.dm^{-3}$) sulfuric acid ($H_2SO_4$), 3% hydrogen peroxide ($H_2O_2$) solution

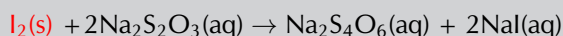
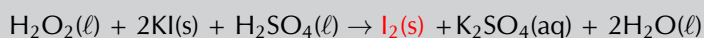
- Five beakers, a measuring cylinder, a hotplate, an ice bath, a glass stirring rod, a stop-watch

**Method:**

- Preheat the hotplate to 40 °C
- Label a beaker solution *1*. Measure 75 ml $H_2SO_4$ into the beaker. Add 25 ml 3% $H_2O_2$. Remember to use dilute (0,2 $mol.dm^{-3}$) sulfuric acid.

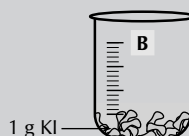
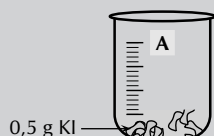
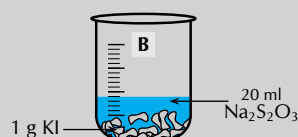
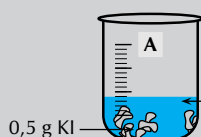
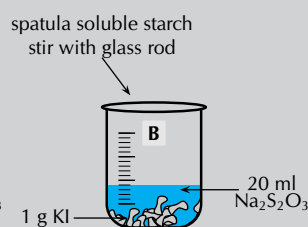
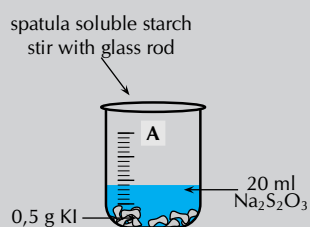
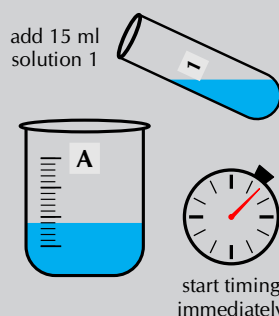
The equations for what is occuring in this reaction are given below:

$$H_2O_2(\ell) + 2KI(s) + H_2SO_4(\ell) \rightarrow I_2(s) + K_2SO_4(aq) + 2H_2O(\ell)$$

$$I_2(s) + 2Na_2S_2O_3(aq) \rightarrow Na_2S_4O_6(aq) + 2NaI(aq)$$

It is good scientific practice to vary only one factor at a time during an experiment. Therefore, this experiment has two parts. First we will vary the concentration of KI, then we will vary the temperature:

- **Varying the concentration**

1. Weigh out 0,5 g of KI into a beaker and label it *A*.

2. Weigh out 1 g of KI into a different beaker and label it *B*.

3. Add 20 ml $Na_2S_2O_3$ to both beaker A and beaker B.

4. Add a spatula of soluble starch to both beaker A and beaker B and stir with a glass rod.

5. Measure 15 ml of solution *1* with the measuring cylinder. Get your stopwatch ready. Pour the 15 ml of solution 1 into beaker A and start timing.

   Stop timing when the solution starts to change colour. Write down your time in the table below.

add 15 ml solution 1

start timing immediately

6. Repeat step 5 with beaker B.

| Beaker | Concentration (M) | Temperature (°C) | Time (s) |
|---|---|---|---|
| A | approx. 0.15 | room temperature | |
| B | approx. 0.3 | room temperature | |

- **Varying the temperature**

  1. Weigh out 0,5 g of KI into a new beaker and label it *C*.
  2. Add 20 ml $Na_2S_2O_3$ to beaker C.
  3. Add a spatula of soluble starch to beaker C and stir with a glass rod.
  4. Measure 15 ml of solution *1* with the measuring cylinder.
  5. *Place beaker C in the ice bath*.
  6. Get your stopwatch ready. Pour the 15 ml of solution 1 into beaker C and start timing. Stop timing when the solution starts to change colour. Write down your time in the table below.
  7. Repeat steps 1 - 4 (label the beaker *D*).
     *Place beaker D on the hotplate*. Then repeat step 6

| Beaker | Concentration (M) | Temperature (°C) | Time (s) |
|---|---|---|---|
| A | approx. 0.15 | room temperature | |
| C | approx. 0.15 | 0 | |
| D | approx. 0.15 | 40 | |

  Beaker A has been included here because it has the same concentration as beakers C and D, but is at a different temperature.

**Results:**

Make a table with the information for all the beakers. Include columns for concentration, temperature, time, and reaction rate.

**Questions and discussion:**

- Did beaker A or B have the faster reaction rate?
- Why did it have a faster reaction rate?
- Did beaker A, C or D have the fastest reaction rate? Why?
- Did beaker A, C or D have the slowest reaction rate? Why?

**Conclusions:**

You will notice that the faster reaction rate occurs in the beaker with the higher concentration of KI. You should also see that the higher the temperature, the faster the reaction rate.

See video: 27TV at www.everythingscience.co.za

This video shows how this experiment can be used as a clock with the concentration chosen so that the experiment changes colour at a specific time (or with a particular part of a song). This is why this experiment is known as the *iodine clock reaction*.

See video: 27TW at www.everythingscience.co.za

**Worked example 2: Reaction rates**

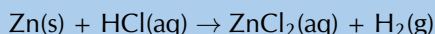
***QUESTION***

Write a balanced equation for the exothermic reaction between Zn(s) and HCl($\ell$). Also name three ways to increase the rate of this reaction.

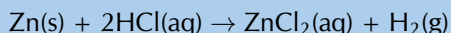
*SOLUTION*

**Step 1: Write the equation for zinc and hydrochloric acid**

The products must be a salt and hydrogen gas. Zinc ions have a charge of 2+ while chloride ions have a charge of 1-. Therefore the salt must be $ZnCl_2$.

$Zn(s) + HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$

**Step 2: Balance the equation if necessary**

There are more chloride ions and hydrogen atoms on the right side of the equation. Therefore there must be 2 HCl on the left side of the equation.

$Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$

**Step 3: Think about the methods mentioned in this section that would increase reaction rate**

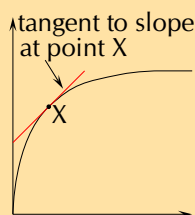
- A catalyst could be added
- The zinc solid could be ground into a fine powder to increase its surface area
- The HCl concentration could be increased

**Exercise 7 – 3: Rates of reaction**

1. Hydrochloric acid and calcium carbonate react according to the following equation: $CaCO_3(s) + 2HCl(\ell) \rightarrow CaCl_2(s) + H_2O(\ell) + CO_2(g)$

   The volume of carbon dioxide that is produced during the reaction is measured at different times. The results are shown in the table below.

| Time (mins) | Total Volume of $CO_2$ produced ($cm^3$) |
|---|---|
| 1 | 14 |
| 2 | 26 |
| 3 | 36 |
| 4 | 44 |
| 5 | 50 |
| 6 | 58 |
| 7 | 65 |
| 8 | 70 |
| 9 | 74 |
| 10 | 77 |

*Note: On a graph of production against time, it is the gradient of the tangent to the graph that shows the rate of the reaction at that time.*
e.g.

   a) Use the data in the table to draw a graph showing the volume of gas that is produced in the reaction, over a period of 10 minutes.
   (Remember to label the axes and plot the graph on graphing paper)
   b) At which of the following times is the reaction *fastest*: 1 minute; 6 minutes or 8 minutes. Explain.
   c) Suggest a reason why the reaction slows down over time.

d) Use the graph to estimate the volume of gas that will have been produced after 11 minutes.

e) How long do you think the reaction will take to stop (give a time in minutes)?

f) If the experiment was repeated using a more concentrated hydrochloric acid solution:

i. would the average rate of the reaction increase or decrease from the one shown in the graph?

ii. draw a line on the same set of axes to show how you would expect the reaction to proceed with a more concentrated HCl solution.

2. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27TX

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## 7.3 Measuring rates of reaction ESCN3

How the average rate of a reaction is measured will depend on what the reaction is, what the reactants are, and what product forms. Look back at the reactions that have been discussed so far. In each case, how was the average rate of the reaction measured? The following examples will give you some ideas about other ways to measure the average rate of a reaction:

### Measuring the volume of gas produced per unit time ESCN4

The volume of gas produced in a reaction may be measured by collecting the gas in a gas syringe (Figure 7.4).

As more gas is produced, the plunger is pushed out and the volume of the gas in the syringe can be recorded.

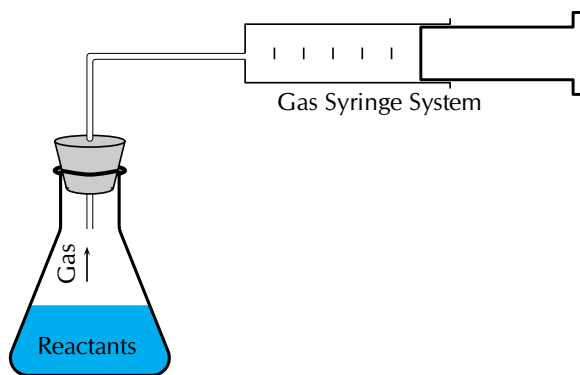



Figure 7.4: The gas syringe method.

See video: 27TY at www.everythingscience.co.za

By measuring the volume at set time intervals, we can graph the data (Figure 7.5) and hence determine the rate of the reaction.

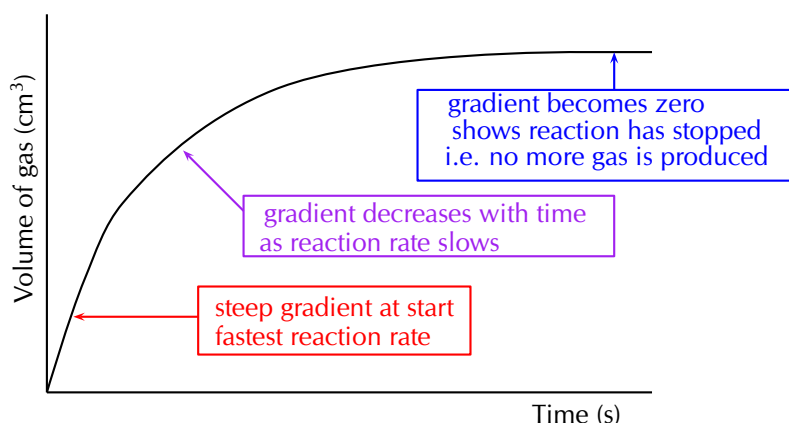



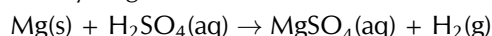
Figure 7.5: A plot of the volume of gas collected at set time intervals.

Examples of reactions that produce gas are listed below:

- *Reactions that produce hydrogen gas:*

  When a *metal reacts with an acid*, hydrogen gas is produced. The hydrogen can be collected in a test tube. A **lit splint** can be used to test for hydrogen. The '**pop**' sound shows that hydrogen is present.

  For example, magnesium reacts with sulfuric acid to produce magnesium sulfate and hydrogen.

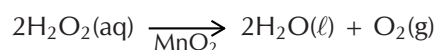
  $Mg(s) + H_2SO_4(aq) \rightarrow MgSO_4(aq) + H_2(g)$

- *Reactions that produce carbon dioxide:*

  When a *carbonate reacts with an acid*, carbon dioxide gas is produced. When carbon dioxide is passed through **limewater**, it turns the limewater **milky**. A burning splint will also **stop burning** (be extinguished) in the presence of $CO_2$ gas. These are a simple tests for the presence of carbon dioxide.

  For example, calcium carbonate reacts with hydrochloric acid to produce calcium chloride, water and carbon dioxide.

  $CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + H_2O(\ell) + CO_2(g)$

- *Reactions that produce oxygen:*

  Hydrogen peroxide decomposes in the presence of a manganese(IV) oxide catalyst to produce oxygen and water.

  $2H_2O_2(aq) \xrightarrow[MnO_2]{} 2H_2O(\ell) + O_2(g)$

**Experiment: Measuring reaction rates**

**Aim:**

To measure the effect of concentration on the average rate of a reaction.

**Apparatus:**

- Solid zinc granules, 1 $mol.dm^{-3}$ hydrochloric acid (HCl)
- Two conical flasks, two beakers, two balloons, bunsen burner, splint of wood

**Method:**

**WARNING!**

---

**Do not get hydrochloric acid (HCl) on your hands. We suggest you use gloves and safety glasses whenever handling acids and handle with care.**

---

**FACT**
When the reaction between two liquids forms an insoluble compound, solid material will form in the liquid. This solid is called a precipitate.

1. Label a conical flask *A*. Weigh 5 g zinc granules into it.

   Repeat with the second conical flask but label it *B*.

2. Label a beaker *1*. Pour 10 $cm^3$ HCl into it.

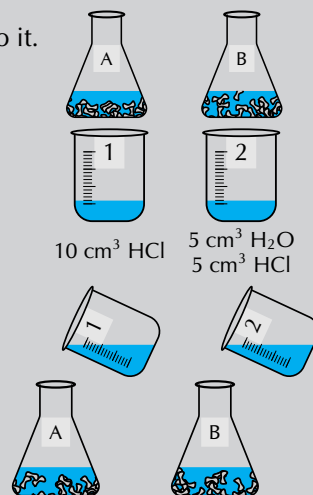
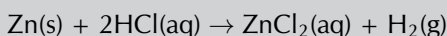
   Label the other beaker *2*. Pour 5 $cm^3$ $H_2O$ into it. Add 5 $cm^3$ HCl to this second beaker.

3. **Quickly:** Pour the liquid in beaker **1** into conical flask **A** and pour the liquid in beaker **2** into conical flask **B**. Attach one balloon firmly to each conical flask.

4. Note which balloon filled more quickly.

5. Fill a test tube with the gas formed. Light **only** the gas in the test tube. Keep open flames away from the balloons.

   The equation for this reaction is:

   $Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$

**Results:**

- Which beaker contained the more concentrated solution of HCl?
- Which balloon filled more quickly?
- What happened when you lit the gas in the test tube?

**Conclusions:**

The more concentrated solution led to a faster reaction rate (i.e. the balloon filling with $H_2$ gas more quickly). The test for hydrogen gas would have resulted in a loud *pop* when the lit splint was placed near the mouth of a test tube.

See video: 27TZ at www.everythingscience.co.za

## Precipitate reactions ESCN5

In reactions where a *precipitate* is formed, the amount of precipitate formed in a period of time can be used as a measure of the reaction rate. For example, when sodium thiosulfate reacts with an acid, a yellow precipitate of sulfur is formed. The reaction is as follows:

$Na_2S_2O_3(aq) + 2HCl(aq) \rightarrow 2NaCl(aq) + SO_2(aq) + H_2O(\ell) + S(s)$

One way to estimate the average rate of this reaction is to carry out the investigation in a conical flask and to place a piece of paper with a black cross underneath the bottom of the flask. At the beginning of the reaction, the cross will be clearly visible when you look into the flask (Figure 7.6). However, as the reaction progresses and more precipitate is formed, the cross will gradually become less clear and will eventually disappear altogether. Measuring the time that it takes for this to happen will give an idea of the reaction rate. Note that it is not possible to collect the $SO_2$ gas that is

produced in the reaction, because it is very soluble in water.

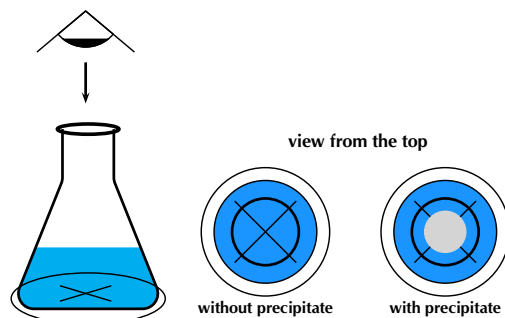



Figure 7.6: At the beginning of the reaction between sodium thiosulfate and hydrochloric acid, when no precipitate has been formed, the cross at the bottom of the conical flask can be clearly seen. As the precipitate forms less of it can be seen.

**Informal experiment: Measuring reaction rates**

**Aim:**

To measure the effect of concentration on the average rate of a reaction.

**Apparatus:**

- 300 $cm^3$ of sodium thiosulfate $Na_2S_2O_3$ solution. (Prepare a solution of sodium thiosulfate by adding 12 g of $Na_2S_2O_3$ to 300 $cm^3$ of water). This is solution 'A'.
- 300 $cm^3$ of water
- 100 $cm^3$ of 1:10 dilute hydrochloric acid. This is solution 'B'.
- Six 100 $cm^3$ glass beakers, measuring cylinders, paper and marking pen, stop-watch or timer

**Method:**

**WARNING!**

---

**Do not get hydrochloric acid (HCl) on your hands. We suggest you use gloves and safety glasses whenever handling acids and that you handle with care.**

---

One way to measure the average rate of this reaction is to place a piece of paper with a cross underneath the reaction beaker to see how long it takes until the cross cannot be seen due to the formation of the sulfur precipitate.

1. Set up six beakers on a flat surface and label them 1 to 6.
2. Pour 60 $cm^3$ solution A into the first beaker and add 20 $cm^3$ of water
3. Place the beaker on a piece of paper with a large black cross on it.
4. Use the measuring cylinder to measure 10 $cm^3$ HCl. Now add this HCl to the solution that is already in the first beaker (NB: Make sure that you always clean the measuring cylinder you have used before using it for another chemical).
5. Using a stopwatch with seconds, write down the time it takes for the precipitate that forms to block out the cross.
6. Now measure 50 $cm^3$ of solution A into the second beaker and add 30 $cm^3$ of water. Place the beaker over the black cross on the paper. To this second beaker, add 10 $cm^3$ HCl, time the reaction and write down the results as you did before.
7. Continue the experiment by diluting solution A as shown below.

| Beaker | Solution A ($cm^3$) | Water ($cm^3$) | Solution B ($cm^3$) | Time (s) |
|---|---|---|---|---|
| 1 | 60 | 20 | 10 | |
| 2 | 50 | 30 | 10 | |
| 3 | 40 | 40 | 10 | |
| 4 | 30 | 50 | 10 | |
| 5 | 20 | 60 | 10 | |
| 6 | 10 | 70 | 10 | |

The equation for the reaction between sodium thiosulfate and hydrochloric acid is:

$Na_2S_2O_3(aq) + 2HCl(aq) \rightarrow 2NaCl(aq) + SO_2(aq) + H_2O(\ell) + S(s)$

**Results:**

- Calculate the reaction rate in each beaker. Remember that:

  $$\text{rate of the formation of product} = \frac{\text{moles product formed}}{\text{reaction time (s)}}$$

  In this experiment you are stopping each experiment when the same approximate amount of precipitate is formed (the cross is blocked out by precipitate). So a relative reaction rate can be determined using the following equation:

  $$\text{reaction rate} = \frac{1}{\text{time (s)}}$$

- Represent your results on a graph. **Concentration** will be on the x-axis and **reaction rate** on the y-axis. Note that the original volume of $Na_2S_2O_3$ can be used as a measure of concentration.
- Why was it important to keep the volume of HCl constant?
- Describe the relationship between concentration and reaction rate.

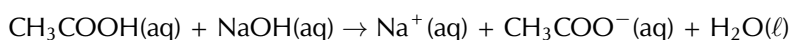
**Conclusions:**

The higher the concentration of the reactants, the faster the average reaction rate.

## Changes in colour ESCN6

In some reactions there is a change in colour which tells us that the reaction is occurring. The faster the colour change the faster the reaction rate.

For example, when ethanoic acid (acetic acid) is titrated with sodium hydroxide, an indicator such as phenolphthalein is added. The solution is clear in an acidic solution and changes to pink when the reaction is complete. If the concentration of the base were increased, the colour change would happen faster (after a smaller volume of base was added), showing that a higher concentration of base increased the reaction rate.

$CH_3COOH(aq) + NaOH(aq) \rightarrow Na^+(aq) + CH_3COO^-(aq) + H_2O(\ell)$

## Changes in mass ESCN7

For a reaction that produces gas, the mass of the reaction vessel can be measured over time. The mass loss indicates the amount of gas that has been produced and escaped from the reaction vessel (Figure 7.7).

If the reaction vessel is sealed this method will not work.

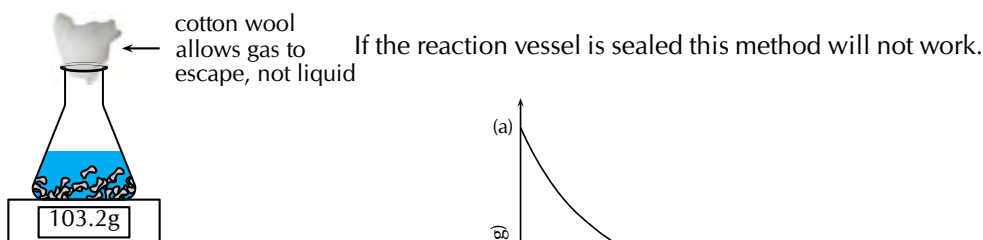



Figure 7.7: A change in mass indicating the loss of a gas

(photo by tjmwatson on Flickr).

Figure 7.8: **a)** A graph of the sample mass versus time and **b)** a graph of the mass loss versus time.

Notice the difference between the two graphs in Figure 7.8. The mass of the sample will decrease as the reaction proceeds. The mass lost from the sample will increase as the reaction proceeds. The material lost (that accounts for the mass loss) can be collected and measured (for example with the gas syringe method as shown in Figure 7.4).

## 7.4 Mechanism of reaction and catalysis ESCN8

Earlier it was mentioned that it is the *collision* of particles that causes reactions to occur and that only some of these collisions are successful. This is because the reactant particles have a wide range of kinetic energies, and only a small fraction of the particles will have enough energy (and the correct orientation) to actually break bonds so that a chemical reaction can take place. The minimum energy that is needed for a reaction to take place is called the **activation energy**. For more information on the energy of reactions, refer to Grade 11 (Chapter 12).

### Activation Energy ESCN9

**DEFINITION:** *Activation energy*

The minimum energy required for a chemical reaction to proceed.

Even at a fixed temperature, the energy of the particles varies, meaning that only some of them will have enough energy to be part of the chemical reaction, depending on the activation energy for that reaction (Figure 7.9). Increasing the reaction temperature has the effect of increasing the number of particles with enough energy to take part in the reaction, and increasing the reaction rate.

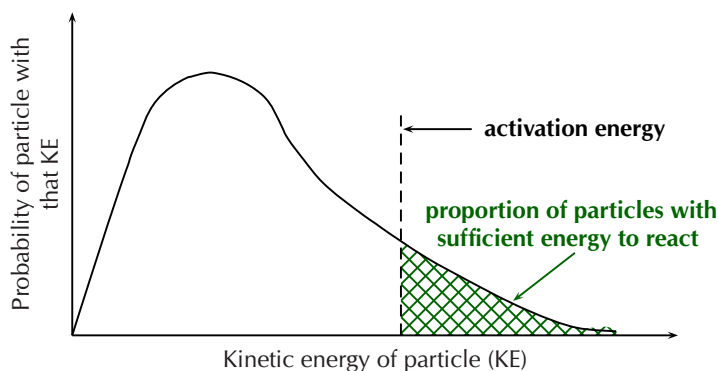



Figure 7.9: The distribution of particle kinetic energies at a fixed temperature.

Remember that a molecule must have energy greater than the activation energy, as well as the correct orientation, for the reaction to take place.

Increasing the temperature of a reaction mixture raises the average kinetic energy of the particles. As can be seen on the graph (Figure 7.10), a higher proportion of the particles can now react making the reaction faster. With the increased movement of the molecules the chances of a molecule having the correct orientation is also increased.

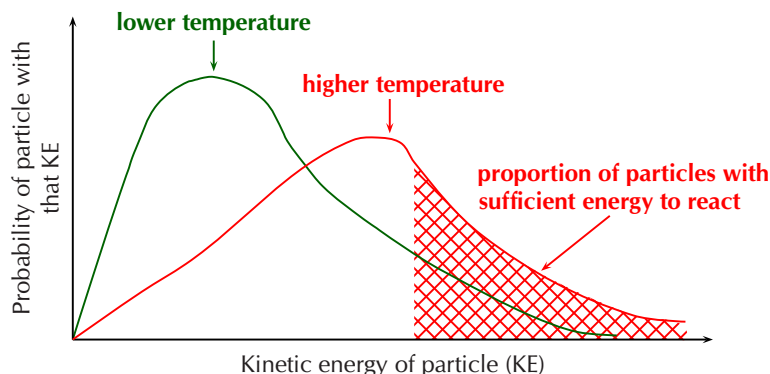



Figure 7.10: The distribution of particle kinetic energies with an increase in temperature. There is an increased number of particles with sufficient energy due to the higher temperature.

An *endothermic* reaction can be represented by:

Reactants + Energy → Products i.e. a reaction that absorbs energy

This can be shown in an activation energy diagram (Figure 7.11). These graphs are also sometimes called a reaction profile or a potential energy graph.

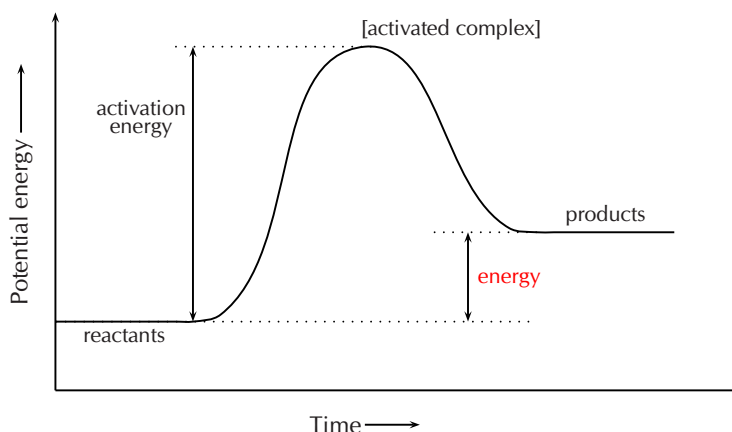



Figure 7.11: An activation energy diagram with reactant energy lower than product energy, i.e. *endothermic*

An *exothermic* reaction can be represented by:

Reactants → Products + Energy     i.e. a reaction that releases energy

This can be shown in an activation energy diagram (Figure 7.12):

**TIP**
An activated complex occurs in reactions without catalysts as well as those with catalysts.

Figure 7.12: An activation energy diagram with reactant energy greater than product energy, i.e. *exothermic*

Revise this section from Grade 11 (Activation energy, Section 12.3).

## How do catalysts work? ESCNB

A **catalyst** increases reaction rates in a slightly different way from other methods of increasing reaction rate. The function of a catalyst is to lower the activation energy so that a greater proportion of the particles have enough energy to react. A catalyst can lower the activation energy for a reaction by:

- orienting the reacting particles in such a way that successful collisions are more likely
- reacting with the reactants to form an intermediate that requires lower energy to form the product

Some *metals* e.g. platinum, copper and iron can act as catalysts in certain reactions. In our own bodies, we have *enzymes* that are catalysts, which help to speed up biological reactions. Catalysts generally react with one or more of the reactants to form a chemical intermediate, which then reacts to form the final product. The chemical intermediate is sometimes called the **activated complex**.

The following is an example of how a reaction involving a catalyst might proceed. A and B are reactants, C is the catalyst, and D is the product of the reaction of A and B.

**Step 1:** A + C → AC     **Step 2:** B + AC → ACB     **Step 3:** ACB → C + D

ACB represents the intermediate chemical. Although the catalyst (C) is consumed by reaction 1, it is later released again by reaction 3, so that the overall reaction with a catalyst is as follows:

A + B + C → D + C

You can see from this that the catalyst is released at the end of the reaction, completely unchanged. Without a catalyst the overall reaction would be:

A + B → D

The catalyst has provided an alternative set of reaction steps, which we refer to as an alternative pathway. The pathway involving the catalyst requires less activation energy and is therefore faster. This can be seen in the following diagram (Figure 7.13).

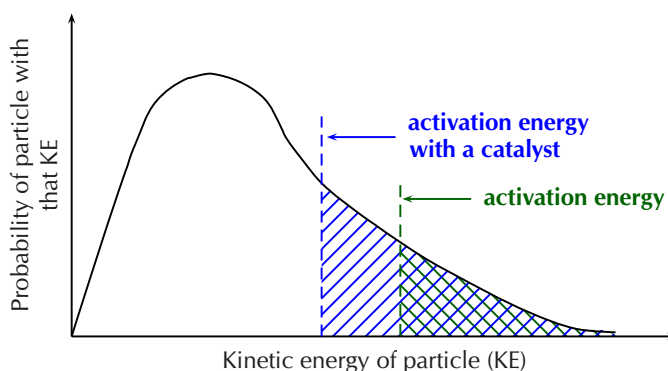



Figure 7.13: The proportion of particles that have enough energy to react is increased in the presence of a catalyst.

**DEFINITION:** *Catalyst*

A catalyst speeds up a chemical reaction, without being consumed by the reaction. It increases the reaction rate by lowering the activation energy for a reaction.

Energy diagrams are useful to illustrate the effect of a **catalyst** on reaction rates. Catalysts decrease the activation energy required for a reaction to proceed (shown by the smaller magnitude of the activation energy on the energy diagram in Figure 7.14), and therefore increase the reaction rate. Remember that with a catalyst, the average kinetic energy of the molecules remains the same but the required energy decreases (Figure 7.13).

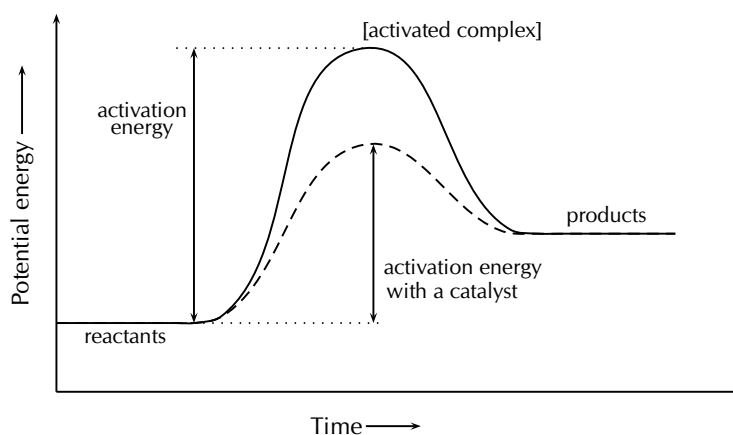



Figure 7.14: The effect of a catalyst on the activation energy of an endothermic reaction. The catalyst would act in the same way for an exothermic reaction.

**Exercise 7 – 4: Reaction rates**

1. For each of the following, say whether the statement is **true** or **false**. If it is false, re-write the statement correctly.
   a) A catalyst increases the energy of reactant molecules so that a chemical reaction can take place.

b) Increasing the temperature of a reaction has the effect of increasing the number of reactant particles that have more energy than the activation energy.

c) A catalyst does not become part of the final product in a chemical reaction.

2. 5 g of zinc pieces are added to 400 $cm^3$ of 0,5 $mol.dm^{-3}$ hydrochloric acid. To investigate the average rate of the reaction, the change in the mass of the flask containing the zinc and the acid is measured by placing the flask on a direct reading balance. The reading on the balance shows that there is a decrease in mass during the reaction. The reaction which takes place is given by the following equation:

   $Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$

   a) Why is there a decrease in mass during the reaction?

   b) The experiment is repeated, this time using 5 g of powdered zinc instead of pieces of zinc. How will this influence the average rate of the reaction?

   c) The experiment is repeated once more, this time using 5 g of zinc pieces and 600 $cm^3$ of 0,5 $mol.dm^{-3}$ hydrochloric acid. How does the average rate of this reaction compare with the **original** reaction rate?

   d) What effect would a catalyst have on the average rate of this reaction?

   (IEB Paper 2 2003)

3. 5 g of calcium carbonate powder reacts with 20 $cm^3$ of a 0,1 $mol.dm^{-3}$ solution of hydrochloric acid. The gas that is produced at a temperature of 25°C is collected in a gas syringe.

   a) Write a balanced chemical equation for this reaction.

   b) The average rate of the reaction is determined by measuring the volume of gas that is produced in the first minute of the reaction. How would the average rate of the reaction be affected if:

      i. a lump of calcium carbonate of the same mass is used

      ii. 20 $cm^3$ of 0,2 $mol.dm^{-3}$ hydrochloric acid is used

4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27V2 2. 27V3 3. 27V4

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## 7.5 Chapter summary ESCNC

See presentation: 27V5 at www.everythingscience.co.za

- The **average rate of a reaction** describes how quickly reactants are used, or how quickly products form. The units used are usually moles per second.
- A number of factors can affect the average rate of a reaction. These include the **nature of the reactants**, the **concentration** of solutions, **surface area** of solids or **pressure** of gases, the **temperature** of the reaction and the presence or absence of a **catalyst**.
- **Collision theory** provides one way of explaining why each of the factors mentioned in the previous bullet can affect the average rate of a reaction. For example, higher temperatures mean increased reaction rates because the reactant

particles have more energy and are more likely to collide successfully with each other.

- Different methods can be used to **measure the average rate of a reaction**. The method used will depend on the nature of the product or products. Reactions that produce gases can be measured by collecting the gas in a syringe or by measuring a change in mass of the reaction vessel. In reactions that produce a precipitate the mass of the dried precipitate can be measured.
- A **change in colour** can show that the **product has formed** or that the **reaction** has reached **completion.** (This is known as colorimetry).
- For any reaction to occur, a minimum amount of energy is needed so that bonds in the reactants can break, and new bonds can form in the products. The minimum energy that is required is called the **activation energy** of a reaction.
- In reactions where the particles do not have enough energy to overcome this activation energy, one of two methods can be used to facilitate a reaction to take place: increase the temperature of the reaction or add a catalyst.
- **Increasing the temperature of a reaction** means that the average energy of the reactant particles increases and they are more likely to have enough energy to overcome the activation energy and the chances of two molecules having the correct orientation are increased.
- A **catalyst** is used to lower the activation energy so that the reaction is more likely to take place. A catalyst does this by providing an alternative, lower energy pathway for the reaction.
- A catalyst therefore **speeds up a reaction** but remains unchanged after the reaction is complete.

**Exercise 7 – 5:**

1. Explain the following:
   a) Reaction rate
   b) Collision theory
   c) Activation energy
   d) Catalyst
2. $2Mg(s) + O_2(g) \rightarrow 2MgO(s)$
   1 g of Mg is oxidised. The reaction takes 1 day to reach completion. Which is the correct reaction rate for the oxidation of Mg?
   a) $2{,}87 \times 10^{-7}$ mol.s$^{-1}$
   b) $1{,}74 \times 10^{-3}$ mol.s$^{-1}$
   c) $4{,}76 \times 10^{-7}$ mol.s$^{-1}$
   d) $3{,}62 \times 10^{-7}$ mol.s$^{-1}$
3. 10 g of magnesium ribbon reacts with a 0,15 mol.dm$^{-3}$ solution of hydrochloric acid at a temperature of 25 °C.
   a) Write a balanced chemical equation for the reaction.
   b) State **two** ways of increasing the average rate of production of $H_2$ (g).
   c) A table of the results is given:

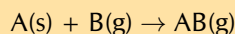
| Time elapsed (min) | Vol of $H_2$(g) (cm$^3$) |
|---|---|
| 0 | 0 |
| 0,5 | 17 |
| 1,0 | 25 |
| 1,5 | 30 |
| 2,0 | 33 |
| 2,5 | 35 |
| 3,0 | 35 |

i. Plot a graph of volume versus time for these results.

ii. Explain the shape of the graph during the following two time intervals: $t = 0$ to $t = 120$ s and then $t = 150$ and $t = 180$ s by referring to the volume of $H_2$ (g) produced.

(IEB Paper 2, 2001)

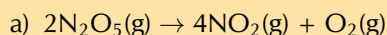
4. Consider the following reaction, which takes place in a closed container:

   $A(s) + B(g) \rightarrow AB(g)$

   If you wanted to increase the average rate of the reaction, which of the following would you do?

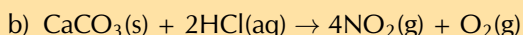
   a) decrease the concentration of B
   b) grind A into a fine powder
   c) decrease the pressure

   (IEB Paper 2, 2002)

5. Consider the following reaction and calculate the reaction rates for the situations that follow:

   a) $2N_2O_5(g) \rightarrow 4NO_2(g) + O_2(g)$

      i. 1,35 mol $N_2O_5$ is used and the reaction goes to completion in 30 minutes.

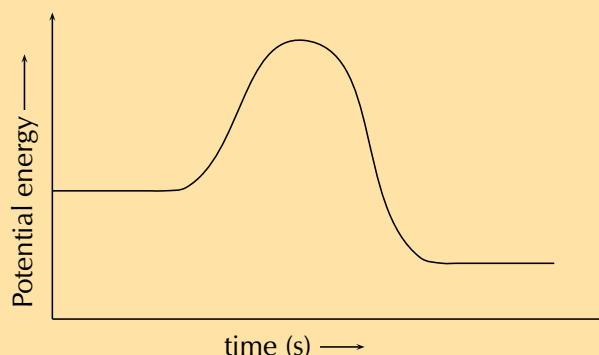
      ii. 2,7 mol $N_2O_5$ is used instead and the reaction goes to completion in 60 minutes.

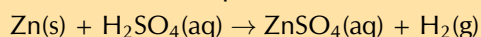
   b) $CaCO_3(s) + 2HCl(aq) \rightarrow 4NO_2(g) + O_2(g)$

      i. 2 g of $CaCO_3$ is placed in excess HCl. The reaction goes to completion over 4 hours.

      ii. The concentration of the HCl is increased and so the reaction takes 2,5 hours instead.

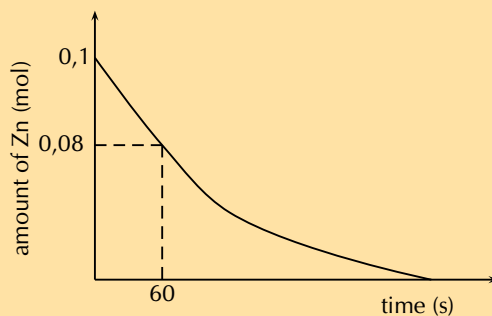
      iii. 3,3 g of $CaCO_3$ is used with a dilute HCl. 0,6 g of solid $CaCO_3$ remains after 4,7 hours.

6. Given:

   A catalyst is added to this reaction. On the same set of axes draw the graph to represent this.

7. A group of learners use the reaction between zinc and sulfuric acid to investigate one of the factors that affects reaction rate. The equation below represents the reaction that takes place.

   $Zn(s) + H_2SO_4(aq) \rightarrow ZnSO_4(aq) + H_2(g)$

   They add 6,5 g of zinc granules to excess *dilute* sulfuric acid and measure the mass of zinc used per unit time.

   The learners then repeat the experiment using excess *concentrated* sulfuric acid.

   The results obtained for the reaction using *dilute* sulfuric acid are represented in the graph below:

a) Define the term *reaction rate*

b) Give a reason why the acid must be in excess

c) Write down a hypothesis for this investigation.

d) Give a reason why the learners must use the same amount of *zinc granules* in both experiments.

e) Using the graph, calculate the mass of zinc used from t = 0 s to t = 60 s.

f) Calculate the average rate of the reaction (in grams per second) during the first 60 s.

g) Copy the above graph and *on the same set of axes* use a dotted line to show the curve that will be obtained when concentrated sulfuric acid is used. No numerical values are required.

(NSC, Paper 2, 2011)

8. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27V6 2. 27V7 3. 27V8 4. 27V9 5. 27VB 6. 27VC
7. 27VD

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CHAPTER

# Chemical equilibrium

Systems in equilibrium are balanced. For example, if you are running on a treadmill you are in constant motion. However, you are not moving forward or backwards. As fast as you run forward the treadmill is moving you backwards. You are in equilibrium with the treadmill.

In the same way chemical reactions can be in equilibrium (the products and reactants are produced at the same rate). We will begin by exploring chemical equilibrium in more detail. Ways of measuring equilibrium and the factors that affect equilibrium will be covered.

## 8.1 What is chemical equilibrium? ESCND

To define chemical equilibrium we need to ask some important questions about reactions:

1. Does a reaction always run its full course so that all the reactants are used up?
   - When all the reactants in a reaction are used up the reaction is said to have **gone to completion**. However, in some reactions not all the reactants are used. **Not all reactions go to completion**.
2. Does a reaction always proceed in the same direction or can it be reversed? In other words, does a reaction always proceed *reactants* → *products*, or is it possible that a reaction will reverse and go *products* → *reactants*?
   - Reactions that go to completion are *irreversible*. However, in some reactions the reactants form products (in a **forward reaction**), and the products can change back into reactants (in a **reverse reaction**).
3. Can a reaction reach a point where reactants are still present, but there does not seem to be any further change taking place in the reaction?
   - In all reactions, as the amount of reactant in a reaction decreases the product is formed more slowly. In a reversible reaction, as the amount of product increases the reactant is formed more quickly. Eventually the rate of the forward reaction (reactants → products) equals the rate of the reverse reaction (products → reactants).

     At this point there **are still reactants present** but there does not *appear* to be any further change taking place. The reaction is said to be in **chemical equilibrium**.

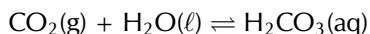
Chemical equilibrium is the state of a reversible reaction where the rate of the forward reaction equals the rate of the reverse reaction. While a reaction is in equilibrium the concentration of the reactants and products are constant.

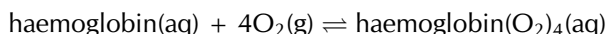
**DEFINITION:** *Chemical equilibrium*

A reaction is in chemical equilibrium when the rate of the forward reaction equals the rate of the reverse reaction.

There are many examples of chemical equilibrium all around you. One example is a bottle of fizzy cooldrink. In the bottle there is carbon dioxide ($CO_2$) dissolved in the liquid. There is also $CO_2$ gas in the space between the liquid and the cap. There is a

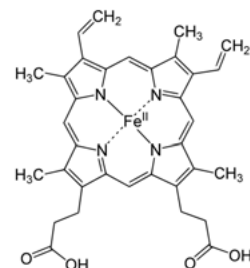
constant movement of $CO_2$ from the liquid to the gas phase, and from the gas phase into the liquid. However, if you look at the bottle there does not appear to be any change. The system is in equilibrium.

$CO_2(g) + H_2O(\ell) \rightleftharpoons H_2CO_3(aq)$

Without chemical equilibrium life as we know it would not be possible. Another example of equilibrium in our everyday lives goes on within our very bodies. Haemoglobin is a macromolecule that transports oxygen around our bodies. Without it we would not survive. The haemoglobin has to be able to take up oxgen, but also to release it and this is done through changes in the chemical equilibrium of this reaction in different places in our bodies.

$\text{haemoglobin}(aq) + 4O_2(g) \rightleftharpoons \text{haemoglobin}(O_2)_4(aq)$

This video is a good demonstration of how a reaction reaches equilibrium with time.

See video: 27VF at www.everythingscience.co.za

**FACT**

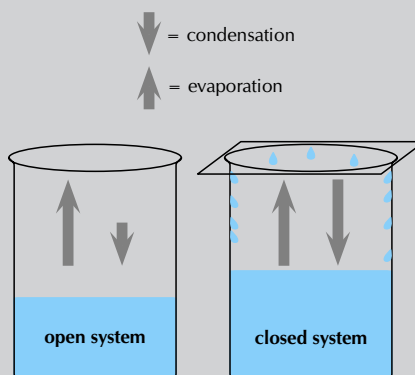
Haemoglobin, inside red blood cells in the lungs, bonds with oxygen. This *oxyhaemoglobin* moves with the red blood cells through the blood stream to cells throughout the body.

## Open and closed systems ESCNF

### Experiment: Liquid-gas phase equilibrium

**Apparatus:**

- 2 beakers, glass cover
- water

**Method:**

1. Half-fill two beakers with water and mark the level of the water in each case.
2. Cover one of the beakers with a glass cover.
3. Leave the beakers and, over the course of a day or two, observe how the water levels in the two beakers change. What do you notice? Note: You could speed up this demonstration by placing the two beakers over a Bunsen burner, or in direct sunlight, to heat the water.

**Observations:**

You should notice that in the beaker that is uncovered, the water level drops more quickly than in the covered beaker. This is because of evaporation. In the beaker that is covered, there is an initial drop in the water level, but after a while evaporation appears to stop and the water level in this beaker is higher than that in the one that is open.

**Discussion:**

In the first beaker, liquid water becomes water vapour as a result of evaporation and the water level drops. A small amount of gas molecules will condense again, but because the gas molecules can escape from the system there is much less condensation than evaporation.

**FACT**
**Evaporation** is when a substance goes from the liquid phase to the gas phase (it evaporates).
**Condensation** is when a substance goes from the gas phase to the liquid phase (it condenses).
The bottle contains water vapour (gas) and water droplets are condensing on the side of the bottle.

In the second beaker, evaporation also takes place. However, in this case, the vapour comes into contact with the surface of the glass cover and it cools and condenses to form liquid water again. This water is returned to the beaker. Once condensation has begun, the rate at which the water level drops will start to decrease. At some point, the rate of evaporation will be equal to the rate of condensation, and there will be no change in the water level in the beaker. This can be represented as follows:

**liquid ⇌ vapour**

In this example, the reaction (in this case, a change in the phase of water) can proceed in either direction. In the forward direction there is a change in phase from liquid to gas, present here as water vapour. A reverse change can also take place, when vapour condenses to form liquid again.

An **open system** is one in which matter or energy can flow into or out of the system. In the liquid-gas demonstration we used, the first beaker was an example of an open system because the beaker could be heated or cooled (a change in *energy*), and water vapour (the *matter*) could evaporate from the beaker.

**FACT**
Generally, some of the molecules at the surface of liquids and solids are moving into the gas phase. This means that matter is leaving the system. However, this is such a small fraction of the total volume of the liquid or solid that a reaction involving only solids or liquids can be considered a closed system.

**DEFINITION:** *Open system*

An *open system* is one whose borders allow the movement of **energy and matter** into and out of the system.

A **closed system** is one in which energy can enter or leave, but matter cannot. The second beaker with the glass cover is an example of a closed system. The beaker can still be heated or cooled, but water vapour cannot leave the system because the glass cover is a barrier. Condensation changes the vapour to liquid and returns it to the beaker. In other words, there is no loss of matter from the system.

**DEFINITION:** *Closed system*

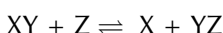
A *closed system* is one in which **only energy** can move into and out of the system. Matter cannot be gained by the system nor lost from the system.

**FACT**
It is useful to simplify situations in science by dividing the world into the *system* we are studying, and the surrounding environment that might influence the reaction, but is not part of it.

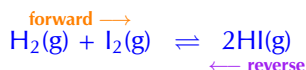
In a **closed system** it is possible for reactions to be reversible, such as in the demonstration above. In a closed system, it is also possible for a chemical reaction to reach **equilibrium**.

## Reversible reactions ESCNG

Some reactions can take place in two directions. In one direction the reactants combine to form the products. This is called the **forward reaction**. In the other direction, the products react to form the reactants again. This is called the **reverse reaction**. A special double-headed arrow ( ⇌ ) is used to show this type of **reversible reaction**:

$XY + Z \rightleftharpoons X + YZ$

**DEFINITION:** *A reversible reaction*

A reversible reaction is a chemical reaction that can proceed in both the forward and reverse directions. In other words, the reactants and products of the reaction may reverse roles.

So, in the following reversible reaction: $H_2(g) + I_2(g) \underset{\longleftarrow \text{ reverse}}{\overset{\text{forward} \longrightarrow}{\rightleftharpoons}} 2HI(g)$

$H_2(g) + I_2(g) \rightarrow 2HI(g)$ is the *forward* reaction.
The forward reaction is always taken from the given equation and written: **left** to **right**.

$2HI(g) \rightarrow H_2(g) + I_2(g)$ is the *reverse* reaction.
The reverse reaction is always taken from the given equation and written: **right** to **left**.

**FACT**
Remember that $\rightarrow$ implies that A goes to B and cannot become A again. $\rightleftharpoons$ implies that the reaction is reversible. A can go to B and B can go to A.

**Exercise 8 – 1: Chemical equilibrium**

1. Which of the following situations describes a closed system?
   a) i. A pot of water (without a lid) heated to 80°C
      ii. A pot of water (with a lid) heated to 80°C
   b) i. $NaCl(aq) + AgNO_3(aq) \rightarrow NaNO_3(aq) + AlCl(s)$ in an open container.
      ii. $2CO(g) + MoO_2(s) \rightarrow 2CO_2(g) + Mo(s)$ in an open container.
2. For the reaction: $A + B \rightleftharpoons C + D$
   a) Write down the forward reaction
   b) Write down the reverse reaction
   c) This reaction is said to be ....... (fill in the missing word)
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27VG 2. 27VH

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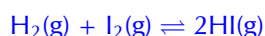
## Dynamic equilibrium ESCNH

We will use the same reversible reaction that we used in an earlier example:

$$H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$$

The forward reaction is: $H_2(g) + I_2(g) \rightarrow 2HI(g)$

The reverse reaction is: $2HI(g) \rightarrow H_2(g) + I_2(g)$

When the rate of the forward reaction and the rate of the reverse reaction are equal, the system is said to be in **equilibrium**. Figure 8.1 shows this. Initially (time = 0), the rate of the forward reaction is high (fast). With time, the rate of the forward reaction decreases. As the reaction gets closer to equilibrium the rate of decrease levels out until the forward reaction has a constant rate.

Initially the rate of the reverse reaction is low (slow). As the reaction proceeds with time, the rate of the reverse reaction increases. As the reaction progresses the rate of increase levels out until the reverse reaction has a constant rate.

At this point the forward and reverse reaction rates are equal and this is called **equilibrium**.

**FACT**
In the equilibrium constant ($K_c$), the subscript *c* refers to the concentration of all the substances at equilibrium.

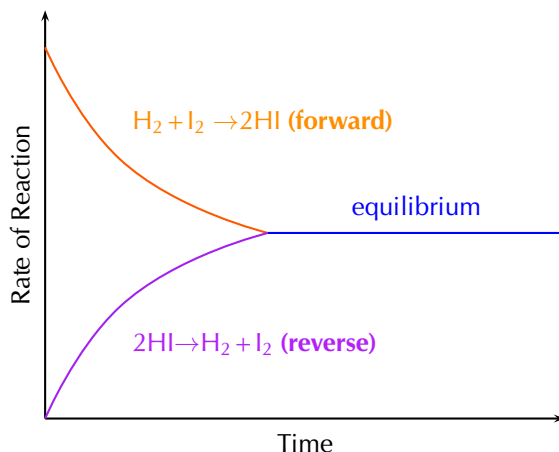
**FACT**
The equation for the equilibrium constant uses the concentrations of the reactants and products. Square brackets mean the concentration of the compound written within the square brackets: **[**x**]** means the concentration of x.

Although it is not always possible to observe any macroscopic changes, this does not mean that the reaction has stopped. The forward and reverse reactions continue to take place and so microscopic changes still occur in the system. This state is called **dynamic equilibrium**.

Figure 8.1: The change in rate of forward and reverse reactions in a closed system.

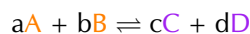
**DEFINITION:** *Dynamic equilibrium*

There is a dynamic equilibrium in a reversible reaction when the rate of the forward reaction equals the rate of the reverse reaction. The amounts of reactants and products remain constant.

In the liquid-gas phase equilibrium demonstration, dynamic equilibrium was reached when there was no observable change in the level of the water in the second beaker even though evaporation and condensation continued to take place.

For more information on dynamic equilibriums watch this video:
See video: 27VJ at www.everythingscience.co.za

## 8.2 The equilibrium constant ESCNJ

Consider the reversible chemical reaction: $aA + bB \rightleftharpoons cC + dD$

A and B are the reactants, C and D are the products and a, b, c, and d are the coefficients from the balanced reaction.

When the rate of the forward reaction equals the rate of the reverse reaction, the system is in chemical equilibrium. It is useful to know how much of each substance is in the container - in particular the amount of products compared to the amount of reactants. A simple ratio from the balanced chemical equation gives us a number called the equilibrium constant ($K_c$).

$$K_c = \frac{[C]^c[D]^d}{[A]^a[B]^b}$$

[A], [B], [C]and[D] are the molar concentrations of each substance present at equilibrium.

**DEFINITION:** *The equilibrium constant*

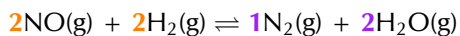
The equilibrium constant ($K_c$) is the ratio between the concentration of products and reactants in a chemical reaction.

When the concentration of the reactants is much larger than the concentration of the products $K_c$ will be small (normally less than one). When the concentration of the reactants is much less than that of the products $K_c$ will be large (normally greater than one).

For example: $2NO(g) + 2H_2(g) \rightleftharpoons N_2(g) + 2H_2O(g)$

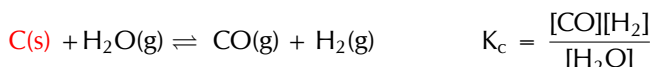
The **reactants** are NO and $H_2$. The **products** are $N_2$ and $H_2O$.

It is important to look at the coefficients of the equation as well:

$2NO(g) + 2H_2(g) \rightleftharpoons 1N_2(g) + 2H_2O(g)$

$K_c$ for this equation will therefore be written as follows: $$K_c = \frac{[N_2]^1[H_2O]^2}{[NO]^2[H_2]^2}$$

In the expression for $K_c$ the concentration of a product or reactant is taken to the power of its coefficient in the balanced reaction. So if the coefficient of a product (C) is 3 in the balanced equation, then the concentration of C ([C]) will be written $[C]^3$ in the expression for $K_c$.

We leave out reactants or products that are either pure **liquids** or in the **solid** phase when calculating $K_c$. For example:

$C(s) + H_2O(g) \rightleftharpoons CO(g) + H_2(g)$ $$K_c = \frac{[CO][H_2]}{[H_2O]}$$

## Calculating the equilibrium constant ESCNK

When calculations involving the equilibrium constant are done, the following tips may help:

1. Always *read the question carefully* to be sure that you understand what you have been asked to calculate.
2. If the equilibrium constant is involved, make sure that the concentrations you use are the concentrations **at equilibrium**, and not the concentrations or quantities that are present at some other time in the reaction.
3. When you are doing more complicated calculations, it helps to draw up a RICE table (Table 8.1). This is gone into in more detail later in this section.

Remember that the general form of the expression for $K_c$ of a reaction at chemical equilibrium ($aA + bB \rightleftharpoons cC + dD$) is: $$K_c = \frac{[C]^c[D]^d}{[A]^a[B]^b}$$

### Worked example 1: Writing expressions for $K_c$

***QUESTION***

For the reaction: $9X(g) + Y_3(g) \rightleftharpoons 3X_3Y(g)$

Write an expression for the equilibrium constant $K_c$.

***SOLUTION***

**Step 1: Write the general expression for $K_c$**

$$K_c = \frac{[C]^c[D]^d}{[A]^a[B]^b}$$

**Step 2: Determine the reactants and the products of the reaction**

$X(g)$ and $Y_3(g)$ are both reactants. They are gases and will be included in the expression. $X_3Y(g)$ is a product. It is a gas and will be included in the expression.

**Step 3: Write the general expression for $K_c$ for this reaction**

$$K_c = \frac{[X_3Y]^z}{[X]^x[Y_3]^y}$$

**Step 4: What are the coefficients in the balanced equation?**

The compound X has a coefficient of **9**. The compound $Y_3$ has a coefficient of **1**. The compound $X_3Y$ has a coefficient of **3**.

**Step 5: Write the expression for $K_c$ for this reaction**

$$K_c = \frac{[X_3Y]^3}{[X]^9[Y_3]^1}$$

### Worked example 2: Calculating reagent concentration

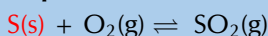
***QUESTION***

For the reaction: $S(s) + O_2(g) \rightleftharpoons SO_2(g)$

1. Write an expression for the equilibrium constant.
2. Calculate the equilibrium concentration of $O_2$ if:
   $K_c = 6$ and $[SO_2] = 3 \text{ mol.dm}^{-3}$ at equilibrium.

***SOLUTION***

**Step 1: Determine which compounds will be part of the $K_c$ expression**

$S(s) + O_2(g) \rightleftharpoons SO_2(g)$

$O_2$ and $SO_2$ are gases and so will be part of the expression for $K_c$. S is solid and so will not be part of the expression for $K_c$.

**Step 2: Write the expression for $K_c$**

$$K_c = \frac{[SO_2]}{[O_2]}$$

**Step 3: Re-arrange the expression so that oxygen is on its own on one side of the expression**

$$[O_2] = \frac{[SO_2]}{K_c}$$

**Step 4: Fill in the values you know and calculate $[O_2]$**

$$[O_2] = \frac{3 \text{ mol.dm}^{-3}}{6} = 0{,}5 \text{ mol.dm}^{-3}$$

### Worked example 3: Calculating $K_c$

***QUESTION***

For the reaction: $SO_2(g) + NO_2(g) \rightleftharpoons NO(g) + SO_3(g)$

The concentrations of the compounds used are:

$[SO_2] = 0{,}2 \text{ mol.dm}^{-3}$, $[NO_2] = 0{,}1 \text{ mol.dm}^{-3}$
$[NO] = 0{,}4 \text{ mol.dm}^{-3}$, $[SO_3] = 0{,}2 \text{ mol.dm}^{-3}$

Calculate the value of $K_c$.

***SOLUTION***

**Step 1: Write the general expression for $K_c$**

$$K_c = \frac{[C]^c[D]^d}{[A]^a[B]^b}$$

**Step 2: Determine the reactants and the products of the reaction**

$SO_2$(g) and $NO_2$(g) are both reactants. They are gases and will be included in the expression.

NO(g) and $SO_3$(g) are both products. They are gases and will be included in the expression.

**Step 3: Write the expression for $K_c$ for this reaction**

All four compounds have a coefficient of **1**.

$$K_c = \frac{[NO]^1[SO_3]^1}{[SO_2]^1[NO_2]^1}$$

**Step 4: Fill in the values you know for this expression and calculate $K_c$**

$$K_c = \frac{(0,4)(0,2)}{(0,2)(0,1)} = 4$$

**TIP**

You do not need to fill in the coefficients in a $K_c$ calculation when they are 1. They are shown here so that you do not forget where the coefficients are reflected in the equation.

When you are doing more complicated calculations, it helps to draw up a RICE table (Table 8.1). A RICE table is an easy way of organising information in equilibrium calculations.

| | | |
|---|---|---|
| **R** | Reaction | the balanced chemical equation |
| **I** | Initial quantity | the moles of reactants and products at the beginning of the reaction |
| **C** | Change | how much the moles of the reactants and products changed between the beginning of the reaction and equilibrium |
| **E** | Equilibrium quantity | the moles of the reactants and products at equilibrium |
| **E** | Equilibrium concentration | to calculate $K_c$ you need the concentration of the reactants and products at equilibrium |

Table 8.1: The use of each row in a RICE.

Here are some guidelines on how to use a RICE table:

1. Fill in the balanced chemical equation: aA + bB $\rightleftharpoons$ cC + dD

| **R**eaction | **aA** | **bB** | **cC** | **dD** |
|---|---|---|---|---|
| **I**nitial quantity (mol) | | | | |
| **C**hange (mol) | | | | |
| **E**quilibrium quantity (mol) | | | | |
| **E**quilibrium concentration ($mol.dm^{-3}$) | | | | |

2. In the **initial** row fill in the number of **moles** of each substance present at the beginning of the reaction. For example, if there are 0,3 moles of A, 0,7 moles of B and no moles of product initially:

| **R**eaction | **aA** | **bB** | **cC** | **dD** |
|---|---|---|---|---|
| **I**nitial quantity (mol) | 0,3 | 0,7 | 0 | 0 |
| **C**hange (mol) | | | | |
| **E**quilibrium quantity (mol) | | | | |
| **E**quilibrium concentration ($mol.dm^{-3}$) | | | | |

3. In the **change** row fill in the number of moles of reactant used, or the number of moles of product formed, in terms of x. Use the balanced equation for this. For example, if dx moles of D is produced, bx moles of B will be used:

| Reaction | $aA$ | $bB$ | $cC$ | $dD$ |
|---|---|---|---|---|
| Initial quantity (mol) | 0,3 | 0,7 | 0 | 0 |
| Change (mol) | -ax | -bx | +cx | +dx |
| Equilibrium quantity (mol) | | | | |
| Equilibrium concentration ($mol.dm^{-3}$) | | | | |

4. In the **equilibrium** row fill in the number of **moles** of each substance present at equilibrium in terms of x. For example, there will be 0,3 - ax moles of A at equilibrium.

| Reaction | $aA$ | $bB$ | $cC$ | $dD$ |
|---|---|---|---|---|
| Initial quantity (mol) | 0,3 | 0,7 | 0 | 0 |
| Change (mol) | -ax | -bx | +cx | +dx |
| Equilibrium quantity (mol) | 0,3 - ax | 0,7 - bx | +cx | +dx |
| Equilibrium concentration ($mol.dm^{-3}$) | | | | |

5. Use any extra information you have been given to calculate x, and then finish filling in the table.

   For example, if the number of moles of B at equilibrium is 0,2:

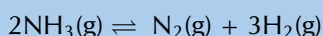
   0,7 - bx = 0,2 and you can solve for x.

6. In the last row fill in the concentration of each substance at equilibrium. You will have to calculate this value.

**Worked example 4: Equilibrium calculations**

***QUESTION***

1,4 moles of $NH_3(g)$ is introduced into a sealed 2,0 $dm^3$ reaction vessel. The ammonia decomposes when the temperature is increased to 600 K and reaches equilibrium as follows:

$$2NH_3(g) \rightleftharpoons N_2(g) + 3H_2(g)$$

When the equilibrium mixture is analysed, the concentration of $NH_3(g)$ is 0,3 $mol.dm^{-3}$.

1. Calculate the concentration of $N_2(g)$ and $H_2(g)$ in the equilibrium mixture.
2. Calculate the equilibrium constant for the reaction at 600 K.

***SOLUTION***

**Step 1: Draw a RICE table**

| Reaction | | | |
|---|---|---|---|
| Initial quantity (mol) | | | |
| Change (mol) | | | |
| Equilibrium quantity (mol) | | | |
| Equilibrium concentration ($mol.dm^{-3}$) | | | |

**Step 2: Fill in the balanced chemical equation on the table:**

| Reaction | $2NH_3$ | $1N_2$ | $3H_2$ |
|---|---|---|---|
| Initial quantity (mol) | | | |
| Change (mol) | | | |
| Equilibrium quantity (mol) | | | |
| Equilibrium concentration ($mol.dm^{-3}$) | | | |

Make sure you know which compounds are the **reactants**, and which are the **products**.

**Step 3: Fill in the number of moles of $NH_3$, $N_2$ and $H_2$ present at the beginning of the reaction**

| Reaction | $2NH_3$ | $1N_2$ | $3H_2$ |
|---|---|---|---|
| Initial quantity (mol) | 1,4 | 0 | 0 |
| Change (mol) | | | |
| Equilibrium quantity (mol) | | | |
| Equilibrium concentration ($mol.dm^{-3}$) | | | |

There are 1,4 mol of $NH_3$, and no moles of $N_2$ or $H_2$ at the beginning of the reaction.

**Step 4: Fill in the change in the number of moles of $NH_3$, $N_2$ and $H_2$ in terms of x**

The mole ratio of $NH_3(g) : N_2 : H_2$ is 2 : 1 : 3.

Therefore, for every 2 moles of $NH_3$ used, 1 mole of $N_2$ and 3 moles of $H_2$ will be formed. If the number of moles of $NH_3$ decreases by 2x ($-2x$), then the number of moles of $N_2$ increases by 1x ($+1x$) and the number of moles of $H_3$ increases by 3x ($+3x$).

| Reaction | $2NH_3$ | $1N_2$ | $3H_2$ |
|---|---|---|---|
| Initial quantity (mol) | 1,4 | 0 | 0 |
| Change (mol) | $-2x$ | $+x$ | $+3x$ |
| Equilibrium quantity (mol) | | | |
| Equilibrium concentration ($mol.dm^{-3}$) | | | |

**Step 5: Fill in the number of moles of $NH_3$, $N_2$ and $H_2$ at equilibrium in terms of x**

| Reaction | $2NH_3$ | $1N_2$ | $3H_2$ |
|---|---|---|---|
| Initial quantity (mol) | 1,4 | 0 | 0 |
| Change (mol) | $-2x$ | $+x$ | $+3x$ |
| Equilibrium quantity (mol) | $1,4 - 2x$ | $+x$ | $+3x$ |
| Equilibrium concentration ($mol.dm^{-3}$) | | | |

To get the number of moles of a substance at equilibrium you take the number of moles initially, and add the change in number of moles in terms of x.

**Step 6: Calculate the value of x**

You know that the concentration of $NH_3$ is 0,3 $mol.dm^{-3}$ at equilibrium and the reaction vessel has a volume of 2 $dm^3$.

$$C = \frac{n}{V}, \text{ therefore } n = C \times V$$

$$n(NH_3 \text{ at equilibrium}) = 0{,}3\ mol.dm^{-3} \times 2{,}0\ dm^3 = 0{,}6\ mol$$

From the RICE table we can see that there are $1,4 - 2x$ moles of $NH_3$ at equilibrium.

$0{,}6\ mol = 1{,}4\ mol - 2x$

$2x = 1{,}4\ mol - 0{,}6\ mol = 0{,}8\ mol$

Therefore, $x = 0{,}4$ mol

**Step 7: Calculate the concentration of $N_2$ formed (at equilibrium).**

From the RICE table we can see that the number of moles of $N_2$ at equilibrium = x

therefore $n(N_2) = 0{,}4$ mol

$$C(N_2) = \frac{n}{V} = \frac{0{,}4\ mol}{2{,}0\ dm^3} = 0{,}2\ mol.dm^{-3}$$

**Step 8: Calculate the concentration of $H_2$ formed (at equilibrium).**

From the RICE table we can see that the number of moles of $H_2$ at equilibrium = 3x

$n(H_2) = 3 \text{ x } 0{,}4\ mol = 1{,}2\ mol$

$$C(H_2) = \frac{n}{V} = \frac{1{,}2\ mol}{2{,}0\ dm^3} = 0{,}6\ mol.dm^{-3}$$

**Step 9: Complete the RICE table**

| Reaction | $2NH_3$ | $1N_2$ | $3H_2$ |
|---|---|---|---|
| Initial quantity (mol) | 1,4 | 0 | 0 |
| Change (mol) | $-2x$ | $+x$ | $+3x$ |
| Equilibrium quantity (mol) | $1,4 - 2x$ | $+x$ | $+3x$ |
| Equilibrium concentration ($mol.dm^{-3}$) | 0,3 | 0,2 | 0,6 |

**Step 10: Write the expression for $K_c$ for this reaction**

$NH_3$ is the reactant, $N_2$ and $H_2$ are the products. They are all in the gas phase, and so are included in the expression for $K_c$.

$$K_c = \frac{[N_2][H_2]^3}{[NH_3]^2}$$

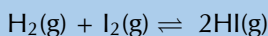
**Step 11: Calculate $K_c$**

$$K_c = \frac{(0,2)(0,6)^3}{(0,3)^2} = 0,48$$

## Worked example 5: Calculating $K_c$

***QUESTION***

Hydrogen and iodine gas react according to the following expression:

$H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$

When 0,496 mol $H_2$ and 0,181 mol $I_2$ are heated at 450°C in a 1 $dm^3$ container, the equilibrium mixture is found to contain 0,00749 mol $I_2$. Calculate the equilibrium constant for the reaction at 450°C.

***SOLUTION***

**Step 1: Draw a RICE table**

| Reaction | | | |
|---|---|---|---|
| Initial quantity (mol) | | | |
| Change (mol) | | | |
| Equilibrium quantity (mol) | | | |
| Equilibrium concentration ($mol.dm^{-3}$) | | | |

**Step 2: Fill in the balanced chemical equation on the table:**

| Reaction | $1H_2$ | $1I_2$ | $2HI$ |
|---|---|---|---|
| Initial quantity (mol) | | | |
| Change (mol) | | | |
| Equilibrium quantity (mol) | | | |
| Equilibrium concentration ($mol.dm^{-3}$) | | | |

**Step 3: Fill in the number of moles of $H_2$, $I_2$ and HI present at the beginning of the reaction**

| Reaction | $1H_2$ | $1I_2$ | $2HI$ |
|---|---|---|---|
| Initial quantity (mol) | 0,496 | 0,181 | 0 |
| Change (mol) | | | |
| Equilibrium quantity (mol) | | | |
| Equilibrium concentration ($mol.dm^{-3}$) | | | |

There are 0,496 moles of $H_2$, 0,181 moles of $I_2$ and no moles HI at the beginning of the reaction.

**Step 4: Fill in the change in the number of moles of $H_2$, $I_2$ and HI in terms of x**

The mole ratio of $H_2 : I_2 : HI$ is 1 : 1 : 2.

Therefore, for every 1 mole of $H_2$ used, 1 mole of $I_2$ is used and 2 moles of HI will be formed. If the number of moles of $H_2$ decreases by x ($-1x$), then the number of moles of $I_2$ also decreases by x ($-1x$) and the number of moles of HI increases by 2x ($+2x$).

| Reaction | $1H_2$ | $1I_2$ | 2HI |
|---|---|---|---|
| Initial quantity (mol) | 0,496 | 0,181 | 0 |
| Change (mol) | -x | -x | +2x |
| Equilibrium quantity (mol) | | | |
| Equilibrium concentration ($mol.dm^{-3}$) | | | |

**Step 5: Fill in the number of moles of $H_2$, $I_2$ and HI at equilibrium in terms of x**

To get the number of moles of a substance at equilibrium you take the number of moles initially, and add the change in number of moles in terms of x.

| Reaction | $1H_2$ | $1I_2$ | 2HI |
|---|---|---|---|
| Initial quantity (mol) | 0,496 | 0,181 | 0 |
| Change (mol) | -x | -x | +2x |
| Equilibrium quantity (mol) | 0,496 - x | 0,181 - x | +2x |
| Equilibrium concentration ($mol.dm^{-3}$) | | | |

**Step 6: Calculate the value of x**

You know that number of moles of $I_2$ at equilibrium is 0,00749 mol. From the RICE table we can see that there are 0,181 - x moles of $I_2$ at equilibrium. Therefore:

$0{,}00749 \text{ mol} = 0{,}181 \text{ mol} - x$

$x = 0{,}181 \text{ mol} - 0{,}00749 \text{ mol} = 0{,}1735 \text{ mol}$

**Step 7: Calculate the concentration of $H_2$ at equilibrium.**

The volume of the container is 1 $dm^3$. From the RICE table we can see that the number of moles of $H_2$ at equilibrium = 0,496 mol - x. Therefore:

$n(H_2) = 0{,}496 \text{ mol} - 0{,}1735 \text{ mol} = 0{,}3225 \text{ mol}$

$$C(H_2) = \frac{n}{V} = \frac{0{,}3225 \text{ mol}}{1 \text{ dm}^3} = 0{,}3225 \text{ mol.dm}^{-3}$$

**Step 8: Calculate the concentration of $I_2$ at equilibrium.**

$$C(I_2) = \frac{n}{V} = \frac{0{,}00749 \text{ mol}}{1 \text{ dm}^3} = 0{,}00749 \text{ mol.dm}^{-3}$$

**Step 9: Calculate the concentration of HI at equilibrium.**

From the RICE table we can see that the number of moles of HI at equilibrium = 2x. Therefore:

$$n(HI) = 2 \times 0{,}1735 \text{ mol} = 0{,}347 \text{ mol}$$

**Step 10: Complete the RICE table**

| Reaction | $1H_2$ | $1I_2$ | 2HI |
|---|---|---|---|
| Initial quantity (mol) | 0,496 | 0,181 | 0 |
| Change (mol) | -x | -x | +2x |
| Equilibrium quantity (mol) | 0,496 - x | 0,181 - x | +2x |
| Equilibrium concentration ($mol.dm^{-3}$) | 0,3225 | 0,00749 | 0,347 |

**Step 11: Write the expression for $K_c$ for this reaction**

$$K_c = \frac{[HI]^2}{[H_2][I_2]}$$

**Step 12: Calculate $K_c$**

$$K_c = \frac{(0,347)^2}{(0,3225)(0,00749)} = 49,85$$

## The meaning of $K_c$ values ESCNM

The formula for $K_c$ has:

- the concentration of the products in the numerator and the concentration of reactants in the denominator
- a $K_c$ value **greater than 1** means that the equilibrium lies **to the right**
  **there are more products than reactants**
- a $K_c$ value **between 0 and 1** means that the equilibrium lies **to the left**
  **more reactants than products**

This has been summarised in Table 8.2. Note that $K_c$ cannot be 0 or less.

Yield describes the quantity of product in the container relative to the maximum product possible.

| $K_c$ value | Equilibrium | Yield |
|---|---|---|
| $K_c > 1$ | to the right | **more products** than reactants |
| $0 < K_c < 1$ | to the left | **more reactants** than products |

Table 8.2: The meaning of $K_c$ values.

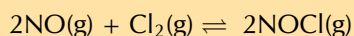
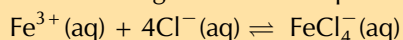
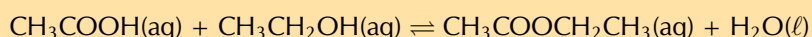
A **high $K_c$** value means that:

- the concentration of products is high
- the equilibrium lies far to the right
- the reaction has a **high yield**

A **low $K_c$ value** (close to 0) means that:

- the concentration of reactants is high
- the equilibrium lies far to the left
- the reaction has a **low yield**

**Exercise 8 – 2: The equilibrium constant**

1. Write the equilibrium constant expression, $K_c$, or balanced chemical equation for the following reactions:
   a) NO and $Cl_2$ are both reactants. NOCl is the product. They are all in the gas state and will be included in the equilibrium constant expression.
      NO has a coefficient of **2**, $Cl_2$ has a coefficient of **1** and NOCl has a coefficient of **2**.
      $2NO(g) + Cl_2(g) \rightleftharpoons 2NOCl(g)$
   b) $K_c = \frac{[H_2O(g)]^2}{[H_2(g)]^2[O_2(g)]}$
2. The following reaction takes place:
   $Fe^{3+}(aq) + 4Cl^-(aq) \rightleftharpoons FeCl_4^-(aq)$
   $K_c$ for the reaction is $7,5 \times 10^{-2}$. At equilibrium, the concentration of $FeCl_4^-(aq)$ is $0,95 \times 10^{-4}$ $mol.dm^{-3}$ and the concentration of $Fe^{3+}(aq)$ is 0,2 $mol.dm^{-3}$. Calculate the concentration of chloride ions at equilibrium.
3. Ethanoic acid ($CH_3COOH$) reacts with ethanol ($CH_3CH_2OH$) to produce ethyl ethanoate and water. The reaction is:
   $CH_3COOH(aq) + CH_3CH_2OH(aq) \rightleftharpoons CH_3COOCH_2CH_3(aq) + H_2O(\ell)$

At the beginning of the reaction, there is 0,5 mol of ethanoic acid and 0,5 mol of ethanol. At equilibrium, 0,3 mol of ethanoic acid was left unreacted. The volume of the reaction container is 2 $dm^3$. Calculate the value of $K_c$.

4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27VK 2. 27VM 3. 27VN

**FACT**

Henry Louis Le Chatelier.

## 8.3 Le Chatelier's principle ESCNN

Any factor that can affect the rate of either the forward or reverse reaction relative to the other can potentially affect the equilibrium position. The following factors can change the chemical equilibrium position of a reaction:

- **concentration**
- **temperature**
- **pressure** (for gaseous reactants)

It is important to understand what effect a change in one of these factors will have on a system that is in chemical equilibrium. However, performing an experiment every time to find out would waste a lot of time. Towards the end of the 1800s the French chemist Henry Louis Le Chatelier came up with principle to predict those effects.

**Le Chatelier's Principle** helps to predict what effect a change in temperature, concentration or pressure will have on the position of the equilibrium in a chemical reaction. This is very important, particularly in industrial applications, where yields must be accurately predicted and maximised. **IMPORTANT!**

### Le Chatelier's Principle

**When an external stress (change in pressure, temperature or concentration) is applied to a system in chemical equilibrium, the equilibrium will change in such a way as to reduce the effect of the stress.**

So if the concentration of one (or more) of the reactants or products is increased the equilibrium will shift to decrease the concentration. Or if the temperature is decreased the equilibrium will shift to increase the temperature by favouring the exothermic reaction. Le Chatelier's principle is that:

- If you change the **concentration** of a reactant then the position of the equilibrium will shift to counteract that change.
- If you change the **temperature** of the reaction the equilibrium will shift to counteract that change.
- If you change the **pressure** of the system the position of the equilibrium will shift to counteract that change.

Each of these concepts is discussed in detail in the following pages.

The following video gives an example of Le Chatelier's principle in action.

See video: 27VP at www.everythingscience.co.za

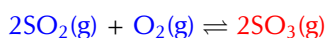
**FACT**
When the concentration of reactants is increased, the equilibrium shifts to the right and there will be more product than before. There will also be more reactants than before (more reactants were added). Once equilibrium has been reestablished (the rate of the forward and reverse reactions are equal again), $K_c$ will be the same as it was before the change to the system. This concept is explained in more detail later in this chapter.

## The effect of concentration on equilibrium ESCNP

If the concentration of a substance is changed, the equilibrium will shift to minimise the effect of that change.

- If the concentration of a **reactant** is **increased** the equilibrium will shift in the direction of the reaction that ***uses*** the reactants, so that the reactant concentration decreases. **The forward reaction is favoured**.
- The forward reaction is also favoured if the concentration of the **product is decreased**, so that more product is formed.
- If the concentration of a **reactant is decreased** the equilibrium will shift in the direction of the reaction that ***produces*** the reactants, so that the reactant concentration increases. **The reverse reaction is favoured**.
- The reverse reaction is also favoured if the concentration of the **product is increased**, so that product is used.

For example, in the reaction between sulfur dioxide and oxygen to produce sulfur trioxide:

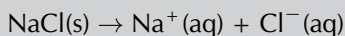
$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$$

- If the $SO_2$ or $O_2$ concentration was **increased**:
  - Le Chatelier's principle predicts that equilibrium will shift to decrease the concentration of reactants.
  - Increasing the rate of the **forward reaction** will mean a decrease in reactants.
  - So some of the sulfur dioxide or oxygen is used to produce sulfur trioxide.
  - Equilibrium shifts to the **right**. That is, when a new equilibrium is reached (when the rate of forward and reverse reactions are equal again), there will be more product than before.
- If the $SO_2$ or $O_2$ concentration was **decreased**:
  - Le Chatelier's principle predicts that the equilibrium will shift to increase the concentration of reactants.
  - Increasing the rate of the **reverse reaction** will mean an increase in reactants.
  - So some sulfur trioxide would change back to sulfur dioxide and oxygen to restore equilibrium.
  - Equilibrium shifts to the **left**. That is, when a new equilibrium is reached there will be less product than before.
- If $[SO_3]$ **decreases**:
  - Le Chatelier's principle predicts that the equilibrium will shift to increase the concentration of products.
  - Increasing the rate of the **forward reaction** will mean an increase in products.
  - So some sulfur dioxide or oxygen is used to produce sulfur trioxide.
  - Equilibrium shifts to the **right**. That is, when a new equilibrium is reached there will be more product than before.
- If $[SO_3]$ **increases**:
  - Le Chatelier's principle predicts that the equilibrium will shift to decrease the concentration of products.
  - Increasing the rate of the **reverse reaction** will mean a decrease in products.
  - So some of the sulfur trioxide would change back to sulfur dioxide and oxygen to restore equilibrium.
  - Equilibrium shifts to the **left**. That is, when a new equilibrium is reached there will be less product than before.

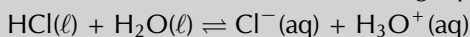
**Extension**

Common-ion effect

In solutions the change in equilibrium position can come about due to the **common-ion effect**. The common-ion effect is where one substance releases ions (upon dissociating or dissolving) which are already present in the equilibrium reaction.

If solid sodium chloride is added to an aqueous solution and dissolves, the following dissociation occurs:

$NaCl(s) \rightarrow Na^{+}(aq) + Cl^{-}(aq)$

If that solution contains the following equilibrium:

$HCl(\ell) + H_2O(\ell) \rightleftharpoons Cl^{-}(aq) + H_3O^{+}(aq)$

The added $Cl^{-}$ ion (common-ion) interferes with the equilibrium by raising the concentration of the $Cl^{-}$ ion. According to Le Chatelier's principle the reverse reaction speeds up as it tries to reduce the effect of the added $Cl^{-}$. As a result the equilibrium position shifts to the left.

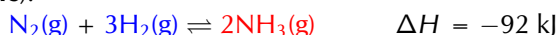
**FACT**
Remember that heat is released during an exothermic reaction. It is a *product* of the reaction.

## The effect of temperature on equilibrium ESCNQ

If the temperature of a reaction mixture is changed, the equilibrium will shift to minimise that change.

- If the temperature is **increased** the equilibrium will shift to favour the reaction which will ***reduce the temperature***. **The endothermic reaction is favoured**.
- If the temperature is **decreased** the equilibrium will shift to favour the reaction which will ***increase the temperature***. **The exothermic reaction is favoured.**

For example the forward reaction shown below is exothermic (shown by the negative value for ΔH). This means that the forward reaction, where nitrogen and hydrogen react to form ammonia, gives off heat, increasing the temperature (**the forward reaction is exothermic**). In the reverse reaction, where ammonia decomposes into hydrogen and nitrogen gas, heat is taken in by the reaction, cooling the vessel (**the reverse reaction is endothermic**).

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \qquad \Delta H = -92 \text{ kJ}$$

- An **increase** in temperature:
  - Favours the **endothermic** reaction because it **takes in** energy (cools the container).
  - The reverse reaction is endothermic, so the **reverse reaction** is favoured.
  - The **yield** of ammonia ($NH_3$) will **decrease**.
- A **decrease** in temperature:
  - Favours the **exothermic** reaction because it **releases** energy (warms the container).
  - The forward reaction is exothermic, so the **forward reaction** is favoured.
  - The **yield** of $NH_3$ will **increase**.

**Informal experiment: Le Chatelier's principle**

**Aim:**

To determine the effect of a change in concentration and temperature on chemical equilibrium

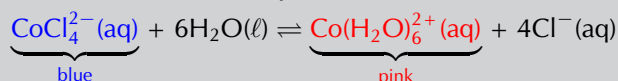
**Apparatus:**

- 0,2 mol.dm$^{-3}$ purple $CoCl_2$ in ethanol solution, concentrated HCl, water
- test tube, tongs
- ice-bath, water-bath, hot-plate or bunsen burner

**Method:**

1. Place the water bath on the hot-plate and heat.
2. During each step observe and record the colour change that takes place.
3. Put 4 – 5 drops of 0,2 mol.dm$^{-3}$ $CoCl_2$ solution into the test tube.
4. Add 10 – 12 drops of water.
5. Add 20 – 25 drops of concentrated HCl.
6. Place the test tube in the water-bath on the hot-plate (use tongs). Leave for 1 – 2 minutes. Record your observations.
7. Place the test tube in the ice-bath. Leave for 1 – 2 minutes. Record your observations.

The equation for the reaction that takes place is:

$$\underbrace{CoCl_4^{2-}(aq)}_{\text{blue}} + 6H_2O(\ell) \rightleftharpoons \underbrace{Co(H_2O)_6^{2+}(aq)}_{\text{pink}} + 4Cl^-(aq)$$

**Results:**

Complete your observations in the table below, noting the colour changes that take place, and also indicating whether the concentration of each of the ions in solution increases or decreases.

| | Original colour | Final colour | $[CoCl_4^{2-}]$ | $[Co(H_2O)_6^{2+}]$ | $[Cl^-]$ |
|---|---|---|---|---|---|
| Add HCl | | | | | |
| Add $H_2O$ | | | | | |
| Increase temp | | | | | |
| Decrease temp | | | | | |

**Conclusions:**

- Use Le Chatelier's principle to explain the changes that you recorded in the table above.
- Draw a conclusion about the effect of a *change in concentration* of either the reactants or products on the equilibrium position.
- Also draw a conclusion about the effect of a *change in temperature* on the equilibrium position.

See video: 27VQ at www.everythingscience.co.za

## The effect of pressure on equilibrium ESCNR

If the pressure of a gaseous reaction mixture is changed the equilibrium will shift to minimise that change.

- If the pressure is **increased** the equilibrium will shift to favour a **decrease** in pressure.
- If the pressure is **decreased** the equilibrium will shift to favour an **increase** in pressure.

When the volume of a system is decreased (and the temperature is constant), the pressure will increase. There are more collisions with the walls of the container. If there are fewer gas molecules there will be fewer collisions, and therefore lower pressure. The equilibrium will shift in a direction that reduces the number of gas molecules so that the pressure is also reduced. So, to predict in which direction the equilibrium will shift to change pressure you need to look at the number of gas molecules in the balanced reactions.

For example, the equation for the reaction between nitrogen and hydrogen is shown below:

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$$

The ratio in the balanced equation is 1 : 3 : 2. That is, for every 1 molecule of $N_2$ gas there are 3 molecules of $H_2$ gas and 2 molecules of $NH_3$ gas (from the balanced equation). Therefore the ratio is **4 molecules of reactant gas** to **2 molecules of product gas**.

- An **increase** in pressure will:
  - Favour the reaction that **decreases** the number of gas molecules.
  - There are **fewer molecules of product gas** than reactant gas, so the **forward reaction** is favoured.
  - The equilibrium will **shift to the right** and the **yield** of $\mathbf{NH_3}$ will **increase**.
- A **decrease** in pressure will:
  - Favour the reaction that **increases** the number of gas molecules.
  - There are **more molecules of reactant gas**, so the **reverse reaction** is favoured.
  - The equilibrium will **shift to the left** and the **yield** of $\mathbf{NH_3}$ will **decrease**.

Consider illustration in Figure 8.2.

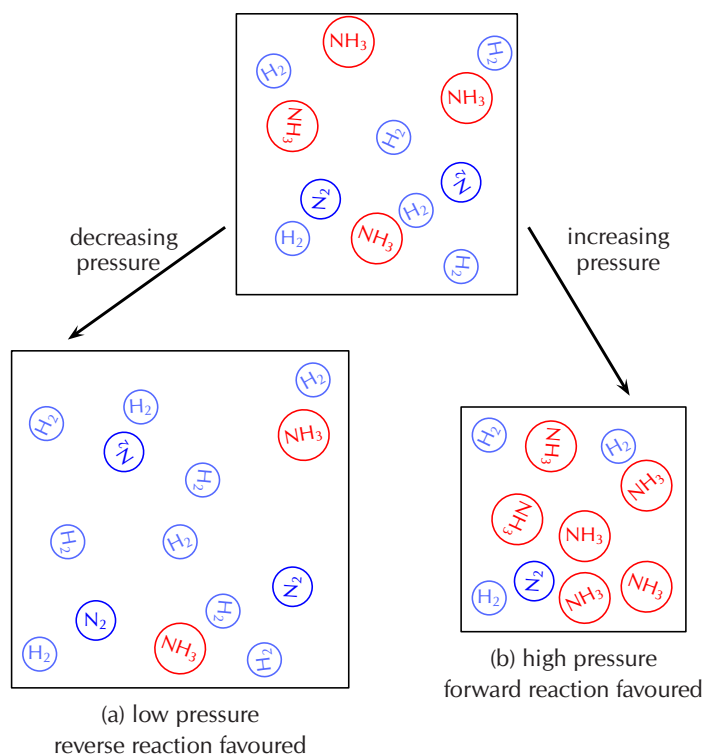



Figure 8.2: **(a)** A decrease in the pressure of this reaction favours the reverse reaction (more gas molecules), the equilibrium shifts to the left. **(b)** An increase in the pressure of this reaction favours the forward reaction (fewer gas molecules), the equilibrium shifts to the right.

**TIP**

Remember from Grade 11 that:

$$p \propto \frac{T}{V}$$

That is, if the temperature remains constant, and the volume is increased, the pressure will decrease.

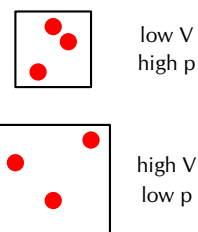



Figure 8.2 shows a decrease in pressure by an increase in the volume, and an increase in pressure by a decrease in the volume.

Figure 8.2 shows how changing the pressure of a system results in a shift in the equilibrium to counter that change. In the original system there are **12** molecules in total:

$$6H_2 + 2N_2 \rightleftharpoons 4NH_3$$

If you **decrease** the pressure (shown by an increase in volume), the equilibrium will shift to **increase** the number of gas molecules. That shift is to the left and the number of $H_2$ and $N_2$ molecules will increase while the number of $NH_3$ molecules will decrease:

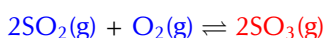
**(a)** $9H_2 + 3N_2 \rightleftharpoons 2NH_3$ total number of molecules = **14**

If you **increase** the pressure (shown by a decrease in volume), the equilibrium will shift to **decrease** the number of gas molecules. That shift is to the right and the number of $H_2$ and $N_2$ molecules will decrease while the number of $NH_3$ molecules will increase:

**(b)** $3H_2 + 1N_2 \rightleftharpoons 6NH_3$ total number of molecules = **10**

Note that the total number of nitrogen and hydrogen atoms remains the same in all three situations. Equations (a) and (b) are not balanced equations.

Another example is the reaction between sulfur dioxide and oxygen:

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$$

In this reaction, **two molecules of product gas** are formed for every **three molecules of reactant gas**.

- An **increase** in pressure will:
  - Favour the reaction that **decreases** the number of gas molecules.
  - There are **fewer molecules of product gas** than reactant gas, so the **forward** reaction is favoured.
  - The equilibrium will **shift to the right** and the **yield** of $SO_3$ will **increase**.
- A **decrease** in pressure will:
  - Favour the reaction that **increases** the number of gas molecules.
  - There are **more molecules of reactant gas** than product gas, so the **reverse** reaction is favoured.
  - The equilibrium will **shift to the left** and the **yield** of $SO_3$ will **decrease**.

## The effect of a catalyst on equilibrium ESCNS

If a catalyst is added to a reaction, both the **forward** and **reverse** reaction rates will be increased. If both rates are increased then the concentrations of the reactants and products will **remain the same**. This means that a catalyst has no effect on the equilibrium position.

However, a catalyst will affect how *quickly equilibrium is reached*. This is very important in industry where the longer a process takes, the more money it costs. So if a catalyst reduces the amount of time it takes to form specific products, it also reduces the cost of production.

## Factors that influence the value of $K_c$ ESCNT

Concentration, pressure, and temperature all affect the equilibrium position of a reaction, and a catalyst affects reaction rates. However, only **temperature** affects the value of $K_c$.

- Changing concentration:
  - Changing the concentration of a reactant or product results in one of the reactions (forward or reverse) being favoured.

- This change in reaction rate minimises the effect of the change and restores the concentration ratio between reactants and products. There will just be more reactants and products.
- $K_c$ will remain the same.

- Changing pressure:
  - Changing the pressure of the system will change the ratio between the reactant and product concentrations.
  - The equilibrium then shifts to minimise the effect of the change and restores the ratio between reactant and product concentrations.
  - $K_c$ will remain the same.
- Adding a catalyst to the system:
  - Both the forward and reverse reactions rates are increased.
  - Therefore the ratio between reactant and product concentrations will remain the same.
  - $K_c$ will remain the same.
- Changing **temperature**:
  - Changing the temperature will favour either the endothermic or exothermic reaction.
  - The ratio between the concentration of the reactants and products will change.
  - $K_c$ **will change**.

**IMPORTANT!**

So make sure that when comparing $K_c$ values for different reactions, the different reactions took place at the same temperature.

## Using Le Chatelier's Principle ESCNV

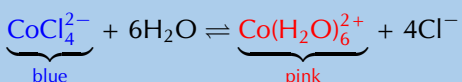
When a system is in chemical equilibrium, and there has been a change in conditions (e.g. concentration, pressure, temperature) the following steps are suggested:

1. Identify the disturbance or stress on the system.
   For example, there is an **increase** in the concentration of reactant.
2. Use Le Chatelier's principle to decide how the system will respond.
   Le Chatelier predicts a shift to **decrease** the concentration of reactant.
3. Look at the given equation and decide whether the rate of the forward reaction or the rate of the reverse reaction is increased. State the shift in equilibrium.
   The **forward reaction will be favoured**. The equilibrium will shift **to the right**.
4. Where appropriate, link equilibrium shift to any observed change in the system.
   This might result in a **colour change**.

**Worked example 6: Using Le Chatelier's principle**

***QUESTION***

Table salt is added to the (purple) solution in equilibrium:

$$\underbrace{CoCl_4^{2-}}_{\text{blue}} + 6H_2O \rightleftharpoons \underbrace{Co(H_2O)_6^{2+}}_{\text{pink}} + 4Cl^-$$

1. Use Le Chatelier's principle to predict the change in equilibrium position.
2. What would be observed?

***SOLUTION***

**Step 1: Identify the disturbance or stress on the system**

Adding NaCl produces $Na^{+}$ ions and $Cl^{-}$ ions as the salt dissolves. Looking at the given equilibrium $Cl^{-}$ is in the equation and the disturbance is the increase in concentration of the $Cl^{-}$ ion.

**Step 2: Use Le Chatelier's principle to decide how the system will respond**

By Le Chatelier's principle, the equilibrium position will shift to reduce the concentration of $Cl^{-}$ ions.

**Step 3: Decide whether the rate of the forward reaction or the rate of the reverse reaction is increased and state the resulting shift in equilibrium**

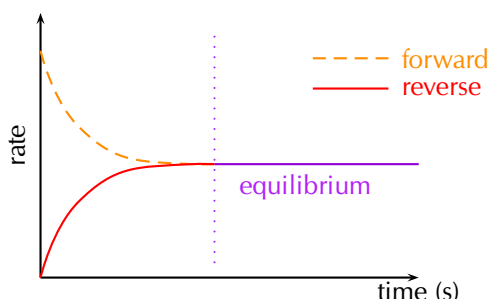
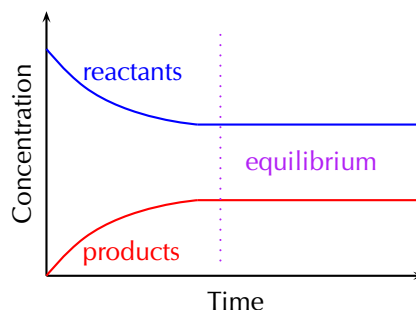
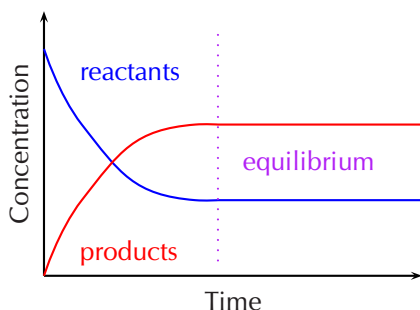
The reverse reaction uses $Cl^{-}$ ions and hence the rate of the reverse reaction will increase. The reverse reaction is favoured and the equilibrium will shift to the left.

**Step 4: What would the colour change be due to this equilibrium shift?**

The solution will appear more blue as more blue $CoCl_4^{2-}$ ions are formed.

### Graphs and Le Chatelier's principle

Graphs can be used to represent data about equilibrium reactions. The following are some points to keep in mind when presented with a graph.

1. Identify the type of graph by looking at the label on the y-axis. You will find either:
   a) a rate-time graph
   b) a mole-time or concentration-time graph
2. For rate-time graphs, when the rate for the forward reaction and the rate for the reverse reaction are equal, the system is in equilibrium.

3. For concentration-time graphs or mole-time graphs equilibrium occurs where the concentration or number of moles of the reactants and products are **constant**. These values need not be equal to one another.

4. When calculating $K_c$ make sure you only take values from the sections of the graph where the y-value is constant. $K_c$ can only be calculated when the system is in equilibrium.

### Rate-time graphs

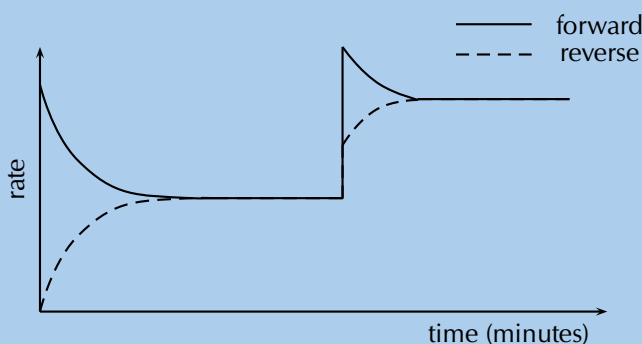
- **A change in concentration** of a substance would favour the reaction that decreases the amount of that substance. This will appear as a sharp increase in the rate of either the forward or reverse reaction and a sharp decrease in the rate of the other reaction.

  The increased rate will then gradually decrease and the decreased rate will gradually increase until they are equal again.
- **A change in pressure** of the reaction would cause a sharp increase or decrease in all the reactants and products. This will have the same effect as a change in concentration, although the increase or decrease would be more gradual.
- **A change in temperature** of a substance would affect both rates in the same direction (either both increase or both decrease). However, the effect will be unequal, with the endothermic reaction favoured by an increase in temperature, and the exothermic reaction favoured by a decrease in temperature.
- **The addition of a catalyst** would favour both the forward and reverse reactions by the same amount.

**Worked example 7: Rate-time graphs**

***QUESTION***

For the reaction $2AB(g) \rightleftharpoons 2A(g) + B_2(g)$, $\Delta H = 26$ kJ the following graph can be plotted:

What stress has occurred in this system? Label the graph with what is happening at each stage.

***SOLUTION***

**Step 1: Check the axes so that you know what the variables are on this graph**

The axes are labelled rate and time. Therefore this is a rate-time graph.

**Step 2: Are the rates both affected in the same way or is one rate increased and the other decreased when the stress is applied?**

Both rates are affected in the same way (increased) therefore the stress must be a catalyst or a change in temperature.

(A change in pressure or concentration would favour one reaction direction only)

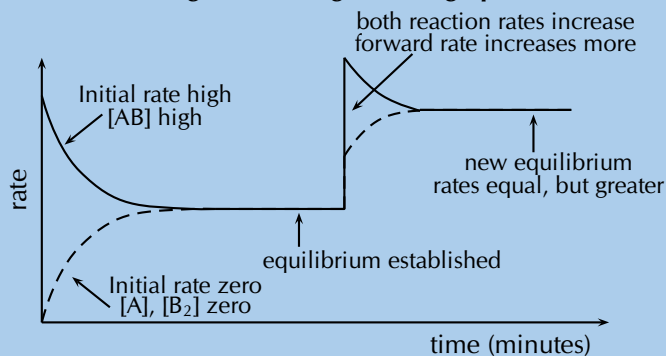
**Step 3: Are both rates affected equally?**

No, the forward rate is increased more than the reverse rate. Therefore the stress must be a change in temperature.

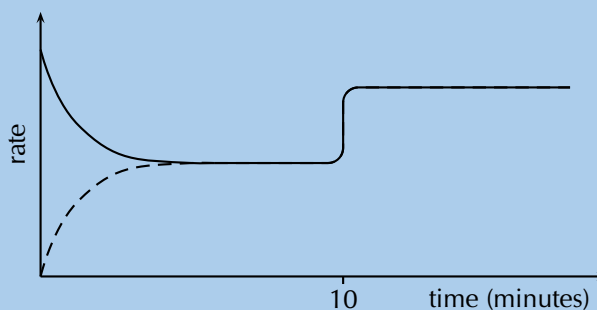
(A catalyst would increase both rates equally)

**Step 4: Was the temperature increased or decreased? (Use Le Chatelier's principle)**

The forward reaction is endothermic ($\Delta H$ is positive). The forward reaction was favoured more than the reverse reaction. An increase in temperature will favour the reaction that cools the reaction vessel (the endothermic reaction). Therefore the stress must have been an increase in temperature.

**Step 5: Label what is occuring at each stage on the graph**

**Worked example 8: Rate-time graphs**

***QUESTION***

What is responsible for the change at t = 10 minutes in the graph below?

***SOLUTION***

**Step 1: Check the axes so that you know what the variables are on this graph**

The axes are labelled rate and time. Therefore this is a rate-time graph.

**Step 2: Are the rates both affected in the same way or is one rate increased and the other decreased when the stress is applied?**

Both rates are affected in the same way (increased) therefore the stress must be a catalyst or a change in temperature.

(A change in pressure or concentration would favour one reaction direction only)

**Step 3: Are both rates affected equally?**

Yes, both rates are increased by the same amount.

**Step 4: What was responsible for the change at t = 10 minutes?**

The addition of a catalyst (a change in temperature would affect both rates, but unequally).

**Concentration-time and mole-time graphs**

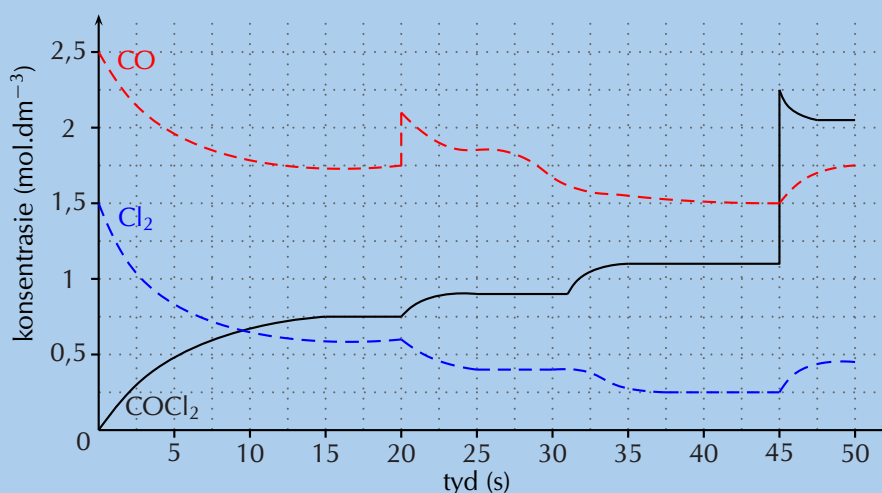
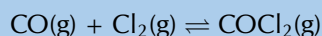
- **A change in concentration** of a substance would appear as a sharp increase or decrease in the concentration or number of moles of that substance and a gradual change in the other substances.
- **A change in temperature** would affect both the forward and reverse reactions. However, one reaction would be affected more than the other. So the reactants and products would be affected gradually, in the opposite direction (one increased, the other decreased).

- **A change in pressure** of the reaction would cause a sharp increase or decrease in all the reactants and products. For an increase in pressure, if the forward reaction is then favoured the reactant concentrations will decrease, and if the reverse reaction is then favoured the product concentrations will decrease.
- **The addition of a catalyst** would increase both the forward and reverse reaction rates, meaning the equilibrium is reached faster. So if the reaction is already at equilibrium there will be no effect on a concentration-time or moles-time graph.

**Worked example 9: Concentration-time graphs**

***QUESTION***

Consider the following chemical equilibrium and graph and answer the questions that follow.

$$CO(g) + Cl_2(g) \rightleftharpoons COCl_2(g)$$

1. How much time was necessary for the system to reach equilibrium for the first time?
2. How do the rates of the forward and reverse reactions compare at the following times:
   - t = 5 s
   - t = 17 s
   - t = 23 s
3. Determine the equilibrium constants for the system at t = 17 s, 25 s, and 45 s.
4. What happens at t = 20 s? Explain your answer by referring to Le Chatelier's principle.
5. What effect does the stress at t = 20 s have on $K_c$?

***SOLUTION***

**Step 1: Check the axes so that you know what the variables are on this graph**

The axes are labelled concentration and time. Therefore this is a concentration-time graph.

**Step 2: How much time was necessary for the system to reach equilibrium?**

The concentration of all three compounds becomes constant at t = 15 s. This means that the reaction has reached equilibrium.

**Step 3: How can you determine which rate is faster from the concentration graphs?**

If the concentrations of the reactants (CO and $Cl_2$) are steadily decreasing or the concentration of the product ($COCl_2$) is increasing then the forward reaction is faster than the reverse reaction.

Similarly, if the concentrations of the reactants (CO and $Cl_2$) are steadily increasing or the concentration of the product ($COCl_2$) is decreasing then the reverse reaction is faster than the forward reaction.

**Step 4: Compare the forward and reverse reaction rates at t = 5 s, t = 17 s and t = 23 s**

At t = 5 s and at t = 23 s the concentrations of the reactants are decreasing and the concentration of the product is increasing. Therefore the rate of the forward reaction is faster than the rate of the reverse reaction.

At t = 17 s the concentrations of the reactants and products are constant (unchanging). Therefore the reaction is in equilibrium and the rate of the forward reaction equals the rate of the reverse reaction.

**Step 5: What are the concentrations of CO, $Cl_2$ and $COCl_2$ at t = 17 s?**

Reading off the graph you can see that:

$[CO] = 1{,}75\ mol.dm^{-3}$ $[Cl_2] = 0{,}6\ mol.dm^{-3}$ $[COCl_2] = 0{,}75\ mol.dm^{-3}$

**Step 6: Write an expression for the equilibrium constant of this reaction and calculate $K_c$.**

$$K_c = \frac{[COCl_2]}{[CO][Cl_2]} \qquad K_c = \frac{0{,}75}{(1{,}75)(0{,}6)} = 0{,}71$$

**Step 7: What happens at t = 20 s?**

The concentration of CO increases sharply. The concentrations of the other compounds do not change dramatically. Therefore CO must have been added to the system.

After this addition of CO there is a shift to reduce the amount of CO, that is in the forward direction. Therefore the concentration of the product increases while the concentrations of the reactants decrease.

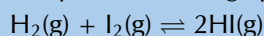
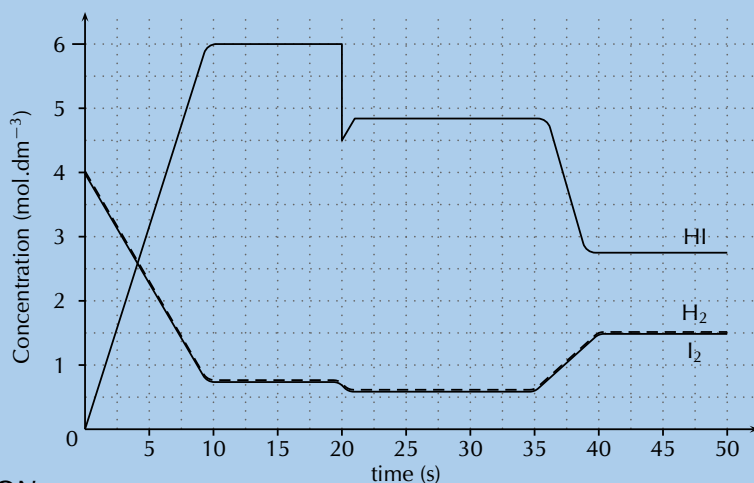
**Step 8: What effect will this have on $K_c$?**

Only a change in temperature affects $K_c$, therefore this will have no effect on $K_c$.

**Worked example 10: Concentration-time graphs**

***QUESTION***

Consider the following chemical equilibrium and graph and answer the questions.

$$H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$$

1. After how many seconds does the system reach equilibrium?
2. Calculate the value of the equilibrium constant.
3. Explain what happened at t = 20 s.
4. If the change at t = 35 s is due to an increase in temperature, is the reaction exothermic or endothermic? Explain your answer.

***SOLUTION***

**Step 1: Check the axes so that you know what the variables are on this graph**

The axes are labelled concentration and time. Therefore this is a concentration-time graph.

**Step 2: After how many seconds does the system reach equilibrium?**

The concentration of all three compounds becomes constant at t = 10 s. This means that the system takes 10 s to reach equilibrium.

**Step 3: What are the concentrations of $H_2$, $I_2$, and HI at t = 10 s, 25 s, and 45 s?**

Reading off the graph you can see that:

At 10 s: $[H_2]$ and $[I_2]$ = 0,75 mol.dm$^{-3}$, [HI] = 6,0 mol.dm$^{-3}$

At 25 s: $[H_2]$ and $[I_2]$ = 0,6 mol.dm$^{-3}$, [HI] = 4,8 mol.dm$^{-3}$

At 45 s: $[H_2]$ and $[I_2]$ = 1,5 mol.dm$^{-3}$, [HI] = 2,75 mol.dm$^{-3}$

**Step 4: Write an expression for the equilibrium constant of this reaction and calculate $K_c$.**

$$K_c = \frac{[HI]^2}{[H_2][I_2]}$$

At t = 10 s: $K_c = \frac{6,0^2}{(0,75)(0,75)} = 64,0$

At t = 25 s: $K_c = \frac{4,8^2}{(0,6)(0,6)} = 64,0$

At t = 45 s: $K_c = \frac{2,75^2}{(1,5)(1,5)} = 3,4$

The different $K_c$ at 45 s means that the event at t = 35 s must be a change in temperature.

**Step 5: Explain what happened at t = 20 s?**

The concentration of HI decreases sharply, as a result there is a slight decrease in the concentration of $H_2$ and $I_2$. Therefore HI must have been removed from the system. After this there is a shift to increase the amount of HI, that is in the forward direction.

**Step 6: If the change at t = 35 s is due to an increase in temperature, is the reaction exothermic or endothermic? Explain your answer.**

An increase in temperature caused the concentration of the product to decrease and the concentrations of the reactants to increase. This means that the reverse reaction has been favoured.

An increase in temperature will favour the reaction that takes heat in and cools the reaction vessel (endothermic). Therefore the reverse reaction must be endothermic and the forward reaction must be exothermic. The reaction is exothermic.

## Summary ESCNW

The following rules will help in predicting the changes that take place in equilibrium reactions:

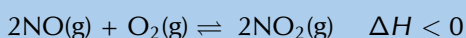
- If the concentration of a **reactant** (on the left) is **increased**, then some of it must be used to form the products (on the right) for equilibrium to be maintained. The equilibrium position will shift to the **right**. $K_c$ is unchanged.
- If the concentration of a **reactant** (on the left) is **decreased**, then some of the products (on the right) must be used to form reactants for equilibrium to be maintained. The equilibrium position will shift to the **left**. $K_c$ is unchanged.
- If the **forward reaction** is **endothermic**, then an **increase** in temperature will favour this reaction and the product **yield** and **$K_c$ will increase**. A **decrease** in temperature will **decrease product yield** and likewise **decrease $K_c$**.
- If the **forward reaction** is **exothermic**, then an **decrease** in temperature will favour this reaction and the product **yield** and **$K_c$ will increase**. An **increase** in temperature will **decrease product yield** and likewise **decrease $K_c$**.
- **Increasing** the pressure favours the side of the equilibrium with the **least number of gas molecules**. This is shown in the balanced chemical equation. This rule applies in reactions with one or more gaseous reactants or products. $K_c$ is unchanged.
- **Decreasing** the pressure favours the side of the equilibrium with **more gas molecules**. This rule applies in reactions with one or more gaseous reactants or products. $K_c$ is unchanged.
- A **catalyst** does not affect the equilibrium position of a reaction. It only influences the *rate of the reaction*, in other words, how quickly equilibrium is reached.

The following simulation will help you to understand these concepts.

See simulation: 27VR at www.everythingscience.co.za

### Worked example 11: Chemical equilibrium

***QUESTION***

$2NO(g) + O_2(g) \rightleftharpoons 2NO_2(g) \quad \Delta H < 0$

How will:

1. the reverse reaction
2. the equilibrium position be affected by:
   a) A decrease in temperature?
   b) The addition of a catalyst?
   c) The addition of more $NO_2$ gas?

***SOLUTION***

1. **The reverse reaction:**
   a) The forward reaction is exothermic ($\Delta H < 0$) so the reverse reaction must be endothermic. A decrease in temperature will cause the equilibrium to shift to favour the exothermic reaction. Therefore the reverse reaction rate will decrease sharply, and then gradually increase until equilibrium is re-established.
   b) The addition of a catalyst will speed up both the forward and reverse reactions.
   c) $NO_2$ is a product. Therefore the addition of more $NO_2$ will increase the

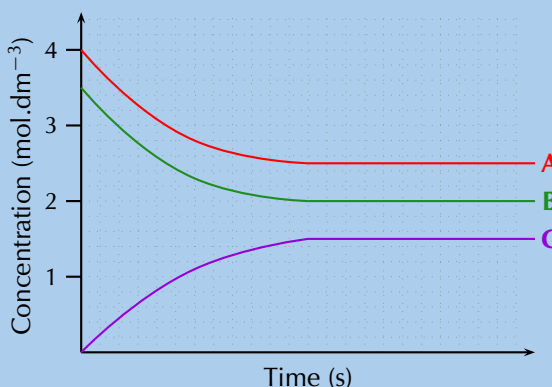
rate of the formation of reactants. The rate of the reverse reaction will therefore increase sharply, and then gradually decrease until equilibrium is re-established.

2. **The equilibrium position:**
   a) A decrease in temperature will favour the exothermic reaction and the forward reaction is exothermic. Therefore the equilibrium position will shift to the right.
   b) The addition of a catalyst will have no effect on the equilibrium position as both the forward and reverse reactions rates would be increased equally.
   c) The addition of more $NO_2$ will favour the formation of the reactants and so the equilibrium will shift to the left.

**Worked example 12: Graphs of equilibrium**

***QUESTION***

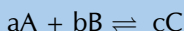
Study the graph and answer the questions that follow:

1. Does the equilibrium favour the reactants or the products?
2. Determine the value of $K_c$ if the coefficients of the balanced equation all equal 1.
3. The forward reaction has $\Delta H > 0$. What effect will an increase in temperature have on [A], [B] and [C]?

***SOLUTION***

**Step 1: Determine which compounds are the reactants and which are the products**

The concentration of reactants decreases from the start of the reaction to equilibrium. Therefore *A* and *B* are reactants.

The concentration of products increases from the start of the reaction to equilibrium. Therefore *C* is a product.

$aA + bB \rightleftharpoons cC$

We are told that all coefficients in the balanced equation equal 1. Therefore the general equation is: $A + B \rightleftharpoons C$

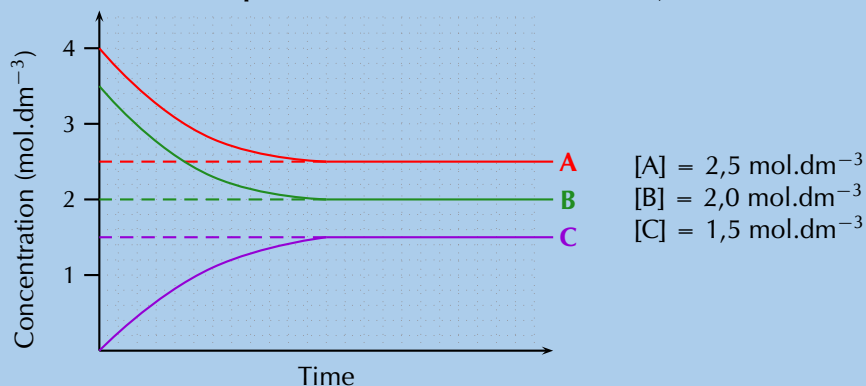
**Step 2: Do reactants or products have higher concentrations at equilibrium?**

A and B (the reactants) have higher concentrations at equilibrium.

**Step 3: Does the equilibrium favour the reactants or products?**

The reactants have higher concentrations than the products, therefore the equilibrium must favour the reactants.

**Step 4: Determine the equilibrium concentration values of A, B and C**

[A] = 2,5 mol.dm$^{-3}$
[B] = 2,0 mol.dm$^{-3}$
[C] = 1,5 mol.dm$^{-3}$

**Step 5: Calculate $K_c$**

$$K_c = \frac{[C]}{[A][B]} = \frac{1,5}{(2,5)(2,0)} = 0,3$$

**Step 6: Determine which reaction is exothermic and which is endothermic**

The forward reaction has $\Delta H > 0$. This means that the forward reaction is endothermic. The reverse reaction must therefore be exothermic.

**Step 7: Which reaction is favoured by an increase in temperature?**

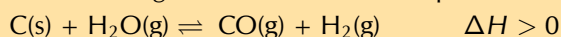
The endothermic reaction would be favoured by an increase in temperature (to lower the temperature). This is the forward reaction.

**Step 8: How would [A], [B] and [C] change?**

The forward reaction is favoured, therefore the equilibrium would shift to the right. This means that the reactant concentrations ([A] and [B]) would decrease and the product concentration ([C]) would increase.

**Exercise 8 – 3: Equilibrium**

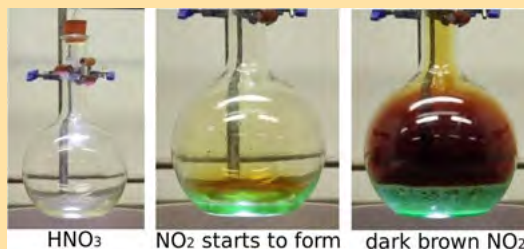
1. The following reaction has reached equilibrium in a closed container:

   $C(s) + H_2O(g) \rightleftharpoons CO(g) + H_2(g) \qquad \Delta H > 0$

   The pressure of the system is then decreased. How will the concentration of the $H_2$ (g) and the value of $K_c$ be affected when the new equilibrium is established?

   | | Hydrogen concentration | $K_c$ |
   |---|---|---|
   | (a) | increases | increases |
   | (b) | increases | stays the same |
   | (c) | stays the same | stays the same |
   | (d) | decreases | stays the same |

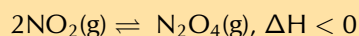
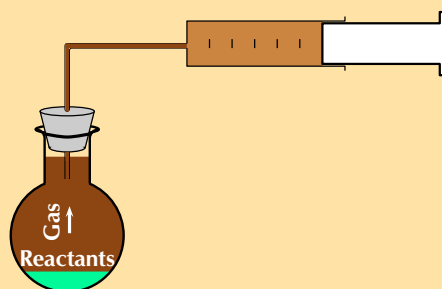
   Assume that the temperature of the system remains unchanged.

   (IEB Paper 2, 2004)

2. During a classroom experiment copper metal reacts with concentrated nitric acid to produce $NO_2$ gas.

   
   

   The $NO_2$ is collected in a gas syringe.

When enough gas has collected in the syringe, the delivery tube is clamped so that no gas can escape. The brown $NO_2$ gas collected reaches an equilibrium with colourless $N_2O_4$ gas as represented by the following equation:

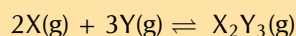
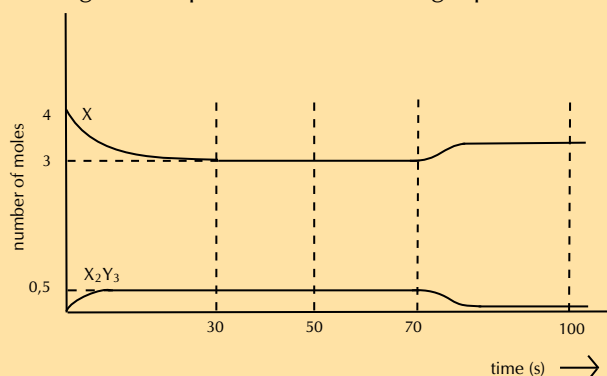
$2NO_2(g) \rightleftharpoons N_2O_4(g)$, $\Delta H < 0$

Once this equilibrium has been established, there are 0,01 moles of $NO_2$ gas and 0,03 moles of $N_2O_4$ gas present in the syringe.

a) A learner, noticing that the colour of the gas mixture in the syringe is no longer changing, comments that all chemical reactions in the syringe must have stopped. Is this assumption correct? Explain.

b) The gas in the syringe is cooled. The volume of the gas is kept constant during the cooling process. Will the gas be lighter or darker at the lower temperature? Explain your answer.

c) The volume of the syringe is now reduced (at constant temperature) to 75 $cm^3$ by pushing the plunger in and holding it in the new position. There are 0,032 moles of $N_2O_4$ gas present once the equilibrium has been re-established at the reduced volume (75 $cm^3$). Calculate the value of the equilibrium constant for this equilibrium.

(IEB Paper 2, 2004)

3. Gases X and Y are pumped into a 2 $dm^3$ container. When the container is sealed, 4 moles of gas X and 4 moles of gas Y are present. The following equilibrium is established:

   $2X(g) + 3Y(g) \rightleftharpoons X_2Y_3(g)$

   The graph shows the number of moles of gas X and gas $X_2Y_3$ that are present from the time the container is sealed.

   a) How many moles of gas $X_2Y_3$ are formed by the time the reaction reaches equilibrium at 30 seconds?

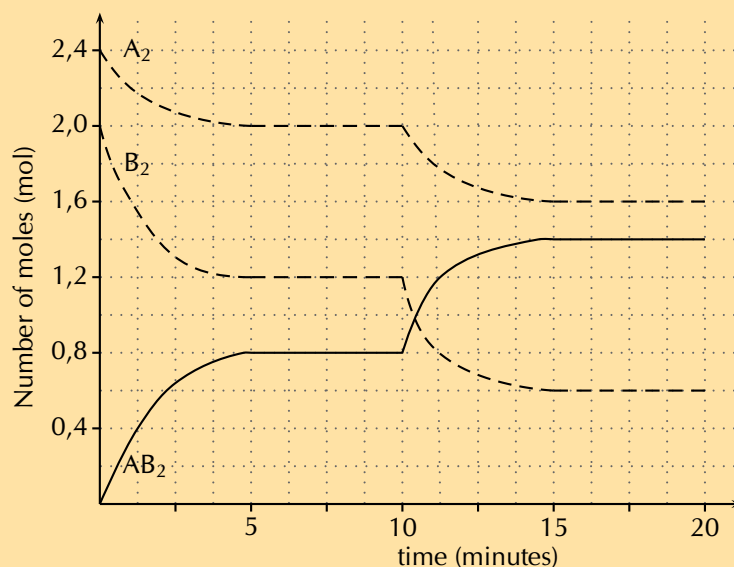
   b) Calculate the value of the equilibrium constant at t = 50 s.

   c) At 70 s the temperature is increased. Is the forward reaction endothermic or exothermic? Explain in terms of Le Chatelier's Principle.

   d) How will this increase in temperature affect the value of the equilibrium constant?

4. Consider the following hypothetical reaction that takes place in a **closed 2 $dm^3$** flask at 298 K.

   $A_2(g) + 2B_2(g) \rightleftharpoons 2AB_2(g)$

   The graph represents the change in the number of moles of each gas in the flask over a period of 20 minutes.

a) State how long (in minutes) it took for the reaction to reach equilibrium for the first time.
b) Write down an expression for the equilibrium constant, $K_c$, for this particular reaction.
c) Calculate the concentration of each of the reactants and the product using figures from the graph between 5 minutes and 10 minutes and hence calculate the equilibrium constant $K_c$ for this reaction at 298 K
d) State what a low value of $K_c$ indicates about the yield of product for a reaction.
e) Why is it not possible to calculate $K_c$ using figures from the graph during the first 5 minutes
f) State Le Chatelier's principle.
g) At 10 minutes the temperature of the flask was increased. Using Le Chatelier's principle, determine if the production of $AB_2$ is exothermic or endothermic?
h) How would the equilibrium **constant** be affected by each of the following changes (state either increase, decrease or no effect):
   i. Increasing the pressure of the flask with no change to temperature.
   ii. Adding a catalyst to the flask.
   iii. Increasing the temperature of the flask.

5. More questions. Sign in at Everything Science online and click 'Practise Science'.

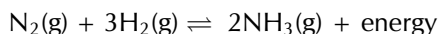
Check answers online with the exercise code below or click on 'show me the answer'.

1. 27VS 2. 27VT 3. 27VV 4. 27VW

## Industrial applications ESCNX

In industrial processes, it is important to get the product as quickly and as efficiently as possible. The less expensive the process the better.

The **Haber process** is a good example of an industrial process which uses the equilibrium principles that have been discussed. The equation for the process is as follows:

$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$ + energy

Since the forward reaction is exothermic, to produce a lot of product and favour the forward reaction the system needs to be colder. However, cooling a system slows down all chemical reactions and so the system can't be too cold. This process is carried out at a much higher temperature to ensure the speed of production.

Because high temperature favours the reverse reaction, the $NH_3$ product is actually removed as it is made (product concentration decreased) to prevent ammonia being used in the reverse reaction. The decrease of product concentration favours the forward reaction.

High pressure is also used to ensure faster reaction time and to favour the production of $NH_3$. The forward reaction is favoured by higher pressures because there are 2 gas molecules of product for every 4 gas molecules of reactant.

Refer to Chapter 14 for more information on the Haber process and other industrial applications.

**Exercise 8 – 4: Applying equilibrium principles**

1. Look at the values of $K_c$ calculated for the Haber process reaction at different temperatures, and then answer the questions that follow:

| *T* (°C) | $K_c$ |
|---|---|
| 25 | $6,4 \times 10^2$ |
| 200 | $4,4 \times 10^{-1}$ |
| 300 | $4,3 \times 10^{-3}$ |
| 400 | $1,6 \times 10^{-4}$ |
| 500 | $1,5 \times 10^{-5}$ |

   a) What happens to the value of $K_c$ as the temperature increases?
   b) Which reaction is being favoured when the temperature is 300 °C?
   c) According to this table, which temperature would be best if you wanted to produce as much ammonia as possible? Explain.

2. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27VX

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## 8.4 Chapter Summary ESCNY

- A reaction is **reversible** when reactants can react to form products, and products can react to form the reactants again.
- A reaction is in **chemical equilibrium** when the rate of the forward reaction equals the rate of the reverse reaction.
- In an **open** system energy and matter can enter and leave the system. In a **closed** system energy can enter and leave the system, but matter cannot.
- The **equilibrium constant** ($K_c$) relates to the concentration of the reactants and products at equilibrium, and can be calculated using the following expression:

  $K_c = \frac{[C]^c[D]^d}{[A]^a[B]^b}$ where $aA + bB \rightleftharpoons cC + dD$

  A and B are reactants, C and D are products and a, b, c, and d are the coefficients of the respective reactants and products.
- A **high $K_c$ value** means that the concentration of products at equilibrium is high

and the reaction has a high yield of the products. A **low $K_c$ value** means that the concentration of products at equilibrium is low and the reaction has a low yield of the products.

- **Le Chatelier's Principle** states that if an external stress (change in pressure, temperature or concentration) is applied to a system in chemical equilibrium, the equilibrium will change in such a way as to reduce the effect of the stress.
- Although a change in temperature, concentration or total pressure will affect the equilibrium position, only **temperature** will affect the equilibrium constant $K_c$.
- The principles of equilibrium are very important in **industrial applications** such as the Haber process, so that productivity can be maximised.

**Exercise 8 – 5:**

1. Explain the following concepts:
   a) Chemical equilibrium
   b) A closed system
   c) A reversible reaction
2. The following equilibrium constant expression is given for a particular reaction: $K_c = \frac{[H_2O]^4[CO_2]^3}{[C_3H_8][O_2]^5}$
   For which one of the following reactions is the above expression of $K_c$ correct?
   a) $C_3H_8(g) + 5O_2(g) \rightleftharpoons 4H_2O(g) + 3CO_2(g)$
   b) $4H_2O(g) + 3CO_2(g) \rightleftharpoons C_3H_8(g) + 5O_2(g)$
   c) $2C_3H_8(g) + 7O_2(g) \rightleftharpoons 6CO(g) + 8H_2O(g)$
   d) $C_3H_8(g) + 5O_2(g) \rightleftharpoons 4H_2O(\ell) + 3CO_2(g)$

   (IEB Paper 2, 2001)
3. Cobalt chloride crystals are dissolved in a beaker containing ethanol and then a few drops of water are added. After a period of time, the reaction reaches equilibrium as follows:
   $CoCl_4^{2-}(aq)(blue) + 6H_2O \rightleftharpoons Co(H_2O)_6^{2+}(aq)(pink) + 4Cl^-$
   The solution, which is now purple, is poured into three test tubes. State, in each case, what colour changes, if any, will be observed if the following are added in turn to each test tube:
   a) 1 $cm^3$ of distilled water
   b) A few crystals of sodium chloride
4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27VY 2. 27VZ 3. 27W2

CHAPTER

# Acids and bases

## 9.1 Acids and bases ESCNZ

### What are acids and bases? ESCP2

We encounter many examples of acids and bases in our daily lives. Some common examples of household items that contain acids are vinegar (contains acetic acid), lemon juice (contains citric and ascorbic acid), wine (contains tartaric acid). These acids are often found to have a sour taste. Hydrochloric acid, sulfuric acid and nitric acid are examples of acids that are more likely to be found in laboratories and industry.

Hydrochloric acid is also found in the gastric juices in the stomach. Fizzy drinks contain carbonic acid, while tea and wine contain tannic acid. People even use acids in an artistic process known as *acid etching*. In acid etching, a metal is covered in a waxy material that is resistant to acid. The bare metal is then exposed in the desired pattern and the sample is placed in an acid bath. The top layers of the exposed metal are permanently removed, creating the desired image. Some examples of this are shown below (Figure 9.2).

acetic acid (in vinegar)

citric acid (in lemons)

tartaric acid (in wine)

Figure 9.1: Some common household acids.

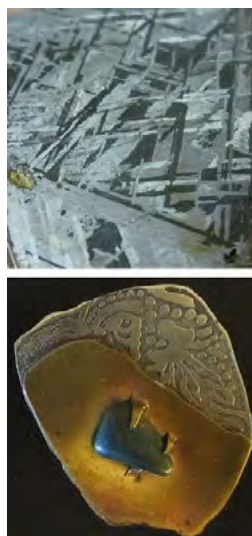



Figure 9.2: Some examples of the acid etching of metal.

Bases that you may know about include sodium hydroxide (commonly known as caustic soda), ammonium hydroxide and ammonia. Some of these are found in household cleaning products. Bases are usually found to have a bitter taste and feel *slippery* (soap is a good example). Acids and bases are also important commercial components in the fertiliser, plastics, and petroleum refining industries. Some common acids and bases, and their chemical formulae, are shown in Table 9.1.

| Acid | Formula | Base | Formula |
|---|---|---|---|
| Hydrochloric acid | $HCl$ | Sodium hydroxide | $NaOH$ |
| Sulfuric acid | $H_2SO_4$ | Potassium hydroxide | $KOH$ |
| Nitric acid | $HNO_3$ | Magnesium hydroxide | $Mg(OH)_2$ |
| Oxalic acid | $H_2C_2O_4$ | Calcium hydroxide | $Ca(OH)_2$ |
| Sulfurous acid | $H_2SO_3$ | Sodium bicarbonate | $NaHCO_3$ |
| Phosphoric acid | $H_3PO_4$ | Sodium carbonate | $Na_2CO_3$ |
| Acetic (ethanoic) acid | $CH_3COOH$ | Ammonium hydroxide | $NH_4OH$ |
| Carbonic acid | $H_2CO_3$ | Ammonia | $NH_3$ |

Table 9.1: Some common acids and bases and their chemical formulae.

**FACT**
The wild lupin plant takes nitrogen from the atmosphere and creates **ammonia**. It uses that ammonia to fertilise the soil for itself and the surrounding plants.

**Activity: Naturally occurring acids and bases**

Do research on three naturally occurring acids, and one naturally occurring base. That is, acids and bases that are found mostly in plants (not man-made).

Your research should include:

- Where the acid or base is found (e.g. the plant in which it occurs).
- Indigenous uses of the plant.
- What the chemical composition of the acid or base is.

**FACT**
Sodium bicarbonate is used in baking. It reacts with the acids in dough to release carbon dioxide. The carbon dioxide then causes the dough to expand.

The next section deals with some models used to describe acids and bases. It is important to have a definition so that acids and bases can be correctly identified in reactions.

## Models for acids and bases ESCP3

For the acids you will encounter this year, an acid is a molecule that donates a $\mathbf{H^+}$ ion.

Substances that will act as a base include hydroxides, oxides, carbonates or hydrogen carbonate, among others. Bases often release free hydroxide ions ($\mathbf{OH^-}$) when dissociating in water.

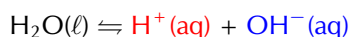
**TIP**
**Dissociation** is the breaking apart of a molecule to form smaller molecules or ions, usually in a reversible manner. For more information on *dissociation*, refer to Grade 10.

### Arrhenius model for acids and bases

A number of models for acids and bases have been developed over the years. One of the earliest was the **Arrhenius** definition. In 1884, Arrhenius discovered that water dissociates (splits up) into hydronium ($H_3O^+$) and hydroxide ($OH^-$) ions according to the following equation:

$$2H_2O(\ell) \rightleftharpoons H_3O^+(aq) + OH^-(aq)$$

Another way of writing this is:

$$H_2O(\ell) \rightleftharpoons H^+(aq) + OH^-(aq)$$

Arrhenius described an acid as a compound that forms $H_3O^+$ when added to water. An Arrhenius acid therefore increases the concentration of $H_3O^+$ ions ( $[H_3O^+]$ ) in water. Arrhenius described a base as a compound that dissociates in water to form $OH^-$ ions. An Arrhenius base therefore increases the concentration of $OH^-$ ions ($[OH^-]$ ) in water.

**DEFINITION:** *Arrhenius acids and bases*

An Arrhenius acid forms $H_3O^+$ in water (increases $[H_3O^+]$). An Arrhenius base forms $OH^-$ in water (increases $[OH^-]$).

**FACT**
Hydrogen atoms contain only one proton. $H^+$ is a hydrogen atom that has lost its electron and is often called a proton.

| | |
|---|---|
| **Arrhenius acid** | increases $[H_3O^+]$ |
| **Arrhenius base** | increases $[OH^-]$ |

Table 9.2: The **Arrhenius** definition of acids and bases.

Look at the following examples showing the dissociation of hydrochloric acid and sodium hydroxide:

1. $HCl(aq) + H_2O(\ell) \rightarrow H_3O^+(aq) + Cl^-(aq)$
   Hydrochloric acid in water increases the concentration of $H_3O^+$ ions and is therefore an *acid*.
2. $NaOH(s) + H_2O(\ell) \rightarrow Na^+(aq) + OH^-(aq) + H_2O(\ell)$
   Sodium hydroxide in water increases the concentration of $OH^-$ ions and is therefore a *base*.

However, this definition can only be used for acids and bases **in water**. Since there are many reactions which do not occur in water, it was important to come up with a much broader definition for acids and bases.

### Brønsted-Lowry model for acids and bases

In 1923, Lowry and Brønsted took the work of Arrhenius further to develop a broader definition for acids and bases. The **Brønsted-Lowry model** defines acids and bases in terms of their ability to donate or accept protons (Table 9.3).

**DEFINITION:** *Brønsted-Lowry acids and bases*

An **acid** is a substance that donates (gives away) protons ($H^+$). A **base** is a substance that accepts (takes) protons.

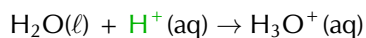
Under the Brønsted-Lowry definition: an acid is a **proton donor**; a base is a **proton acceptor**.

| | | |
|---|---|---|
| **Brønsted-Lowry acid** | donates $H^+$ | proton **donor** |
| **Brønsted-Lowry base** | accepts $H^+$ | proton **acceptor** |

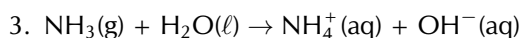
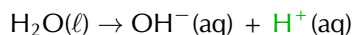
Table 9.3: The **Brønsted-Lowry** definition of acids and bases.

Below are some examples:

1. $HCl(aq) + NH_3(g) \rightarrow NH_4^+(aq) + Cl^-(aq)$
   In order to decide which substance is a proton donor and which is a proton acceptor, we need to look at what happens to each reactant. The reaction can be broken down as follows:
   $HCl(aq) \rightarrow H^+(aq) + Cl^-(aq)$
   - HCl donates a proton.
     It is a *proton donor* and is therefore the **acid**.

   $NH_3(g) + H^+(aq) \rightarrow NH_4^+(aq)$
   - $NH_3$ accepts a proton.
     It is a *proton acceptor* and is therefore the **base**.
2. $CH_3COOH(aq) + H_2O(\ell) \rightarrow H_3O^+(aq) + CH_3COO^-(aq)$
   The reaction can be broken down as follows:
   $CH_3COOH(aq) \rightarrow CH_3COO^-(aq) + H^+(aq)$
   - $CH_3COOH$ donates a proton.
     It is a *proton donor* and is therefore the **acid**.

$H_2O(\ell) + H^+(aq) \rightarrow H_3O^+(aq)$

- Water accepts a proton.
  It is a *proton acceptor* and is therefore the **base**.

3. $NH_3(g) + H_2O(\ell) \rightarrow NH_4^+(aq) + OH^-(aq)$
   The reaction can be broken down as follows:
   $H_2O(\ell) \rightarrow OH^-(aq) + H^+(aq)$

   - Water donates a proton.
     It is a *proton donor* and is therefore the **acid**.

   $NH_3(g) + H^+(aq) \rightarrow NH_4^+(aq)$

   - Ammonia accepts a proton.
     It is a *proton acceptor* and is therefore the **base**.

   Notice that in *example 2* **water** acted as a **base**, while in *example 3* **water** acted as an **acid**. Water can act as both an acid and a base depending on the reaction. A substance that can act as either an acid or a base is called **amphoteric**.

**FACT**
An amphoteric substance that contains both acidic and basic functional groups is called a **ampholyte**.

**DEFINITION:** *Amphoteric*

An amphoteric substance is one that can act as an acid in one reaction, or a base in another reaction.

An **amphiprotic** substance is an amphoteric substance that can donate a proton in one reaction (a Brønsted-Lowry acid), or accept a proton in another reaction (a Brønsted-Lowry base).

**DEFINITION:** *Amphiprotic*

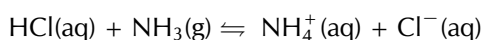
An amphiprotic substance can donate a proton in one reaction, or accept a proton in another reaction.

Substances such as ammonia ($NH_3$), zinc oxide ($ZnO$), and beryllium hydroxide ($Be(OH)_2$) are amphoteric. Water and ammonia are also amphiprotic.

An acid that releases only *one* $H^+$ ion per molecule of acid (e.g. $HCl$) is referred to as **mono**protic. An acid that can release *two* $H^+$ ions per molecule of acid (e.g. $H_2SO_4$) is referred to as **di**protic. Any acid than can donate *more than one* $H^+$ ion per molecule of acid can be referred to as **poly**protic (this means that diprotic acids are also polyprotic).

## Conjugate acid-base pairs ESCP4

Look at the reaction between hydrochloric acid and ammonia to form ammonium and chloride ions:

$HCl(aq) + NH_3(g) \leftrightharpoons NH_4^+(aq) + Cl^-(aq)$

Looking at the **forward reaction** (i.e. the reaction that proceeds from *left* to *right*), the changes that take place can be shown as follows:

- $HCl(aq) \rightarrow Cl^-(aq) + H^+(aq)$
- $NH_3(g) + H^+(aq) \rightarrow NH_4^+(aq)$

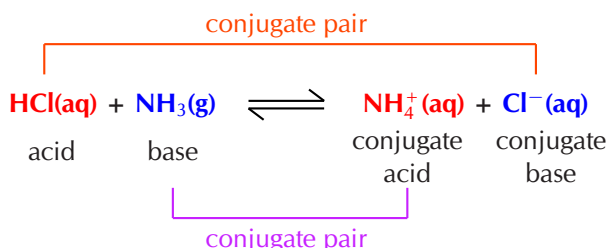
In the *forward reaction*, $HCl$ is a proton donor (**acid**) and $NH_3$ is a proton acceptor (**base**).

Looking at the **reverse reaction** (i.e. the reaction that proceeds from *right* to *left*), the changes that take place are as follows:

- $Cl^{-}(aq) + H^{+}(aq) \rightarrow HCl(aq)$
- $NH_4^{+}(aq) \rightarrow NH_3(g) + H^{+}(aq)$

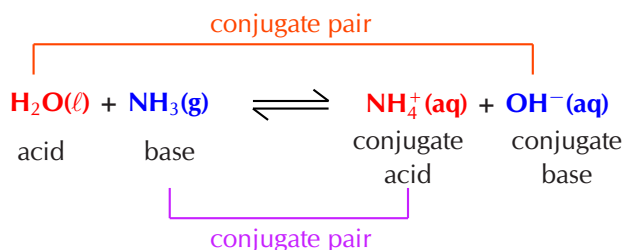
In the *reverse reaction*, the chloride ion ($Cl^{-}$) is the proton acceptor (**base**) and the ammonium ion ($NH_4^{+}$) is the proton donor (**acid**).

In the forward reaction HCl donates a proton ($H^{+}$) to form $Cl^{-}$. In the reverse reaction $Cl^{-}$ accepts a proton to form HCl. $Cl^{-}$ is the conjugate base of the acid HCl. So HCl and $Cl^{-}$ are a **conjugate acid-base pair**.

Similarly, in the forward reaction $NH_3$ accepts a proton ($H^{+}$) to form $NH_4^{+}$. In the reverse reaction $NH_4^{+}$ donates a proton to form $NH_3$. $NH_4^{+}$ is the conjugate acid of the base $NH_3$. So $NH_3$ and $NH_4^{+}$ are a **conjugate acid-base pair**.

The reaction between ammonia and water is another example:

conjugate pair

$$H_2O(\ell) + NH_3(g) \rightleftharpoons NH_4^{+}(aq) + OH^{-}(aq)$$

acid | base | conjugate acid | conjugate base

conjugate pair

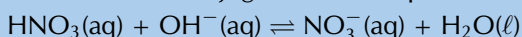
**DEFINITION:** *Conjugate acid-base pair*

A conjugate acid-base pair contains two compounds that differ only by a hydrogen ion ($H^{+}$) and a charge of $+1$.

**Worked example 1: Conjugate acid-base pairs**

***QUESTION***

Determine the conjugate acid-base pairs for the following reaction:

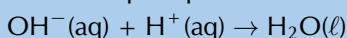
$HNO_3(aq) + OH^{-}(aq) \rightleftharpoons NO_3^{-}(aq) + H_2O(\ell)$

***SOLUTION***

**Step 1: Which reactant is an acid and which is a base?**

$HNO_3$ is nitric acid. It donates a proton in the forward reaction:

$HNO_3(aq) \rightarrow NO_3^{-}(aq) + H^{+}(aq)$

$OH^{-}$ accepts a proton in the forward reaction and is therefore the base:

$OH^{-}(aq) + H^{+}(aq) \rightarrow H_2O(\ell)$

**Step 2: Which product is the conjugate base of the acid?**

Nitric acid ($HNO_3$) donates a proton to become $NO_3^-$. In the reverse reaction $NO_3^-$ accepts a proton to become $HNO_3$. Therefore $NO_3^-$ is the conjugate base of $HNO_3$.

$NO_3^-(aq) + H^+(aq) \rightarrow HNO_3(aq)$

**Step 3: Which product is the conjugate acid of the base?**

$OH^-$ accepts a proton to become $H_2O$. In the reverse reaction $H_2O$ donates a proton to become $OH^-$. Therefore $H_2O$ is the conjugate acid of $OH^-$.

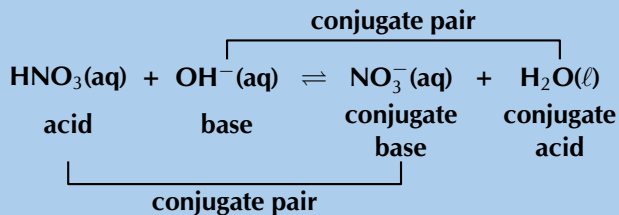
$H_2O(\ell) \rightarrow OH^-(aq) + H^+(aq)$

**Step 4: Label the conjugate acid-base pairs in this reaction**

conjugate pair (base $OH^-$ and conjugate acid $H_2O$)

$$HNO_3(aq) + OH^-(aq) \rightleftharpoons NO_3^-(aq) + H_2O(\ell)$$

acid | base | conjugate base | conjugate acid

conjugate pair (acid $HNO_3$ and conjugate base $NO_3^-$)

## Exercise 9 – 1: Acids and bases

1. In each of the following reactions, label the conjugate acid-base pairs.
   a) $H_2SO_4(aq) + H_2O(aq) \rightleftharpoons H_3O^+(aq) + HSO_4^-(aq)$
   b) $NH_4^+(aq) + F^-(aq) \rightleftharpoons HF(aq) + NH_3(g)$
   c) $H_2O(\ell) + CH_3COO^-(aq) \rightleftharpoons OH^-(aq) + CH_3COOH(aq)$
   d) $H_2SO_4(aq) + Cl^-(aq) \rightleftharpoons HCl(aq) + HSO_4^-(aq)$
2. Write the conjugate base for:
   a) $H_2CO_3$
   b) $H_3O^+$
   c) $H_2PO_4^-$
3. Write the conjugate acid for:
   a) $OH^-$
   b) $CN^-$
   c) $CO_3^{2-}$
4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27W3 2a. 27W4 2b. 27W5 2c. 27W6 3a. 27W7 3b. 27W8 3c. 27W9

## Strong and weak acids and bases ESCP5

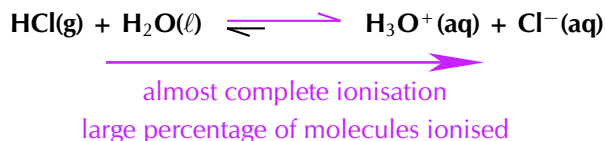
### Strong acids and bases

A strong acid or base is one that will almost completely *dissociate* or *ionise* to form ions in solution. That is, a large percentage of the moles of a strong acid or base will

form ions when added to water.

**DEFINITION:** *Strong acid and strong base*

A **strong** acid or base is one that almost completely dissociates to form ions in solution.

**HCl is a strong acid.** For example if 100 000 molecules of HCl are added to water and 90 000 ionise to form $H^+$ and $Cl^-$ ions, then there is a large amount of ionisation. This is what makes HCl a strong acid.

$$HCl(g) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + Cl^-(aq)$$

almost complete ionisation

large percentage of molecules ionised

The unequal double arrows in the reaction equation indicate that the equilibrium position favours the formation of ions.

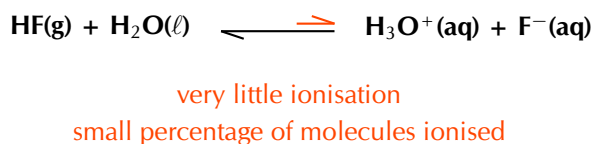
Thee are three strong acids that we commonly find: HCl (hydrochloric acid), $HNO_3$ (nitric acid) and $H_2SO_4$ (sulfuric acid). Two strong bases that are commonly found are: NaOH (sodium hydroxide) and KOH (potassium hydroxide).

### Weak acids and bases

A weak acid or base is one where only a *small percentage* of molecules will dissociate to form ions in solution.

**DEFINITION:** *Weak acid and weak base*

A **weak** acid or base is one where only a small percentage of molecules dissociate to form ions in solution.

**HF is a weak acid.** For example if 100 000 molecules of HF are added to water and only 100 ionise to form $H^+$ and $F^-$ ions, then there is only a small amount of ionisation. This is what makes HF a weak acid.

$$HF(g) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + F^-(aq)$$

very little ionisation

small percentage of molecules ionised

The unequal double arrows in the reaction equation indicate that the equilibrium position does not favour the formation of ions.

An example of a weak base is $Mg(OH)_2$ which will only dissociate partially into $Mg^{2+}$ and $OH^-$ ions.

## Dilute and concentrated solutions ESCP6

A different concept to strong and weak is the concept of **concentrated** and **dilute**. Where strong and weak refer to the characteristic of a compound, concentrated and dilute refer to the characteristic of a solution. Thus a strong acid can be prepared as

either a concentrated or a dilute solution. A solution of which the exact concentration is known is called a **standard solution**.

**DEFINITION:** *Standard solution*

A standard solution is one where the exact concentration of solute in a solvent is known.

### Concentrated solutions

A concentrated solution is one where a large amount of a substance (solute) has been added to a solvent. Note that both strong and weak acids and bases can be used in concentrated solutions.

**DEFINITION:** *Concentrated solution*

A concentrated solution is one where there is a high ratio of dissolved substance (e.g. acid or base) to solvent.

### Dilute solutions

A dilute solution is one where a small amount of a substance has been added to a solvent. Note that both strong and weak acids and bases can be used in dilute solutions.

**DEFINITION:** *Dilute solution*

A dilute solution is one where there is a low ratio of dissolved substance to solvent.

A concentrated solution can be made from a strong or a weak acid or base. A dilute solution can also be made from a strong or a weak acid or base. Whether a solution is concentrated or dilute depends on how much of the acid or base was added to the solvent.

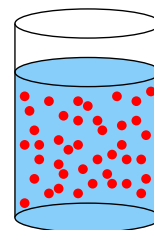
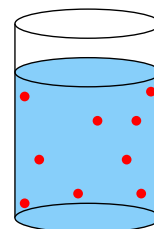
A **strong base** that is also **concentrated** would be a base that **almost completely dissociates** when added to a solution, and you also add a **large amount** of the base to the solution.

A **weak acid** that is also **dilute** would be an acid where only a **small percentage of molecules ionise** when added to a solution, and you also add only a **small amount** of the acid to the solution. Table 9.4 summarises these concepts.

The electrical conductivity of a solution depends on the concentration of **mobile ions** in the solution. This means that a concentrated solution of a strong acid or base will have a high electrical conductivity, while a dilute solution of a weak acid or base will have a low electrical conductivity.

| | Acid | Base |
|---|---|---|
| **Strong** | **high percentage** forms ions in solution | **high percentage** forms ions in solution |
| **Weak** | only a **small percentage** forms ions in solution | only a **small percentage** forms ions in solution |
| **Concentrated** | **large number** of moles of acid in solution | **large number** of moles of base in solution |
| **Dilute** | **small number** of moles of acid in solution | **small number** of moles of base in solution |

Table 9.4: A summary of the properties of strong, weak, concentrated, and dilute acids and bases.

**TIP**

A concentrated solution has a lot of solute molecules (red circles) in the solvent.

A dilute solution has few solute molecules (red circles) in the solvent.

**FACT**

Electric current is the movement of charged particles. Therefore, the more ions (charged particles) there are in a solution, the greater the electric current that can be conducted through the solution by the charged particles. This is the electrical conductivity of a solution.

**TIP**

Mobile ions are ions that are able to move. These include ions in solution and ions in melted ionic materials. The ions in ionic solids are not mobile.

### Worked example 2: Acids and bases

***QUESTION***

Solution 1 contains 100 $dm^3$ of HCl added to 10 $dm^3$ of water. Almost all the HCl molecules ionise in the solution.

Solution 2 contains 0,01 g of $Mg(OH)_2$ added to 1000 $dm^3$ of water. Only a small percentage of the $Mg(OH)_2$ molecules dissociate in the solution.

Say whether these solutions:

1. Contain a strong or weak acid or base.
2. Are concentrated or dilute.

***SOLUTION***

**Step 1: Are the compounds acids or bases?**

HCl is hydrochloric acid. It would donate a proton and is an acid. $Mg(OH)_2$ is magnesium hydroxide and is a base.

**Step 2: What makes an acid or base strong or weak?**

Almost complete ionisation or dissociation means an acid or base is strong. Only a small amount of ionisation or dissociation means an acid or base is weak.

**Step 3: Are the compounds strong or weak acids and bases?**

Almost all the HCl molecules ionise in the solution, therefore HCl is a strong acid.

Only a small percentage of the $Mg(OH)_2$ molecules dissociate, therefore $Mg(OH)_2$ is a weak base.

**Step 4: What makes a solution concentrated or dilute?**

A concentrated solution has a high ratio of solute to solvent. A dilute solution has a low ratio of solute to solvent.

**Step 5: Are the solutions concentrated or dilute?**

100 $dm^3$ of HCl is added to 10 $dm^3$ of water. This is a high ratio, therefore the solution of HCl is concentrated.

0,01 g of $Mg(OH)_2$ is added to 1000 $dm^3$ of water. This is a low ratio, therefore the solution of $Mg(OH)_2$ is dilute.

**Step 6: Combine your information**

Solution 1 is a **concentrated solution** of a **strong acid**.

Solution 2 is a **dilute solution** of a **weak base**.

### Worked example 3: Acids and bases

***QUESTION***

Solution 1 contains 0,01 $dm^3$ of NaOH added to 800 $dm^3$ of water. Almost all the NaOH molecules dissociate in the solution.

Solution 2 contains 100 g of HF added to 10 $dm^3$ of water. Only a small percentage of the HF molecules ionise in the solution.

Say whether these solutions:

1. Contain a strong or weak acid or base.
2. Are concentrated or dilute.

### *SOLUTION*

**Step 1: Are the compounds acids or bases?**

NaOH is sodium hydroxide and is a base. HF is hydrofluoric acid and is an acid.

**Step 2: What makes an acid or base strong or weak?**

Almost complete ionisation or dissociation means an acid or base is strong. Only a small amount of ionisation or dissociation means an acid or base is weak.

**Step 3: Are the compounds strong or weak acids and bases?**

Almost all the NaOH molecules dissociate in the solution, therefore NaOH is a strong base.

Only a small percentage of the HF molecules ionise, therefore HF is a weak acid.

**Step 4: What makes a solution concentrated or dilute?**

A concentrated solution has a high ratio of solute to solvent. A dilute solution has a low ratio of solute to solvent.

**Step 5: Are the solutions concentrated or dilute?**

0,01 g of NaOH is added to 800 $dm^3$ of water. This is a low ratio, therefore the solution of NaOH is dilute.

100 $dm^3$ of HF is added to 10 $dm^3$ of water. This is a high ratio, therefore the solution of HF is concentrated.

**Step 6: Combine your information**

Solution 1 is a **dilute solution** of a **strong base**.

Solution 2 is a **concentrated solution** of a **weak acid**.

**TIP**

Remember, to calculate the concentration of a solution we use the formula:

$$C = \frac{n}{V}$$

**Worked example 4: Calculating concentration**

### *QUESTION*

0,27 g of $H_2SO_4$ is added to 183,7 $dm^3$ of water. Calculate the concentration of the solution.

### *SOLUTION*

**Step 1: List the information you have and the information you need**

$V = 183{,}7\ dm^3$, $m = 0{,}27\ g$

The volume (V) and the mass (m) are given. The number of moles (n) needs to be calculated. To do that the molar mass (M) needs to be calculated.

**Step 2: Make sure all given units are correct and convert them if necessary**

All the units are correct.

**Step 3: What equations will be necessary to calculate the concentration?**

$$C\ (mol.dm^{-3}) = \frac{n\ (mol)}{V\ (dm^3)} \qquad n\ (mol) = \frac{m\ (g)}{M\ (g.mol^{-1})}$$

**Step 4: Calculate the number of moles of the acid in the solution**

$M(H_2SO_4) = (2 \times 1{,}01) + 32{,}1 + (4 \times 16) = 98{,}12\ g.mol^{-1}$.

$$n = \frac{m}{M} = \frac{0{,}27\ g}{98{,}12\ g.mol^{-1}} = 0{,}0028\ mol$$

**Step 5: Calculate the concentration of the solution**

$$C = \frac{n}{V} = \frac{0{,}0028 \text{ mol}}{183{,}7 \text{ dm}^3} = 0{,}0000152 \text{ mol.dm}^{-3} = 1{,}52 \times 10^{-5} \text{ mol.dm}^{-3}$$

**Worked example 5: Calculating concentration**

***QUESTION***

16,4 g of KOH is added to 12,9 $cm^3$ of water. Calculate the concentration of the solution.

***SOLUTION***

**Step 1: List the information you have and the information you need**

$V = 12{,}9 \text{ cm}^3$, $m = 16{,}4 \text{ g}$

The volume (V) and the mass (m) are given. The number of moles (n) needs to be calculated. To do that the molar mass (M) needs to be calculated.

**Step 2: Make sure all given units are correct or convert them**

The volume needs to be converted to $dm^3$.

$$V = 12{,}9 \text{ cm}^3 \times \frac{0{,}001 \text{ dm}^3}{1 \text{ cm}^3} = 0{,}0129 \text{ dm}^3$$

**Step 3: What equations will be necessary to calculate the concentration?**

$$C \text{ (mol.dm}^{-3}) = \frac{n \text{ (mol)}}{V \text{ (dm}^3)} \qquad n \text{ (mol)} = \frac{m \text{ (g)}}{M \text{ (g.mol}^{-1})}$$

**Step 4: Calculate the number of moles of base in the solution**

$M(KOH) = 39{,}1 + 16 + 1{,}01 = 56{,}11 \text{ g.mol}^{-1}$.

$$n = \frac{m}{M} = \frac{16{,}4 \text{ g}}{56{,}11 \text{ g.mol}^{-1}} = 0{,}292 \text{ mol}$$

**Step 5: Calculate the concentration of the solution**

$$C = \frac{n}{V} = \frac{0{,}292 \text{ mol}}{0{,}0129 \text{ dm}^3} = 22{,}64 \text{ mol.dm}^{-3}$$

**Exercise 9 – 2: Types of acids and bases**

1. Say whether the solutions of the acids and bases in the following situations are concentrated or dilute.
    a) For every 1 mole of a solvent there are 50 moles of lithium hydroxide (LiOH).
    b) For every 100 moles of a solvent there are 5 moles of nitric acid ($HNO_3$).
2. 95% of an unknown acid donates protons when the acid is added to water. The pH of the final solution is 6,5.
    a) Is the acid a strong or a weak acid? Give a reason for your answer.
    b) Is a solution with a pH of 6,5 strongly or weakly acidic?
    c) Is the solution concentrated or dilute? Give a reason for your answer.

3. Calculate the concentration for of the following solutions.
   a) 27 g of sodium bicarbonate ($NaHCO_3$) added to 22,6 $cm^3$ of water.
   b) 0,893 mol of phosphoric acid ($H_3PO_4$) added to 4,79 $dm^3$ of a solvent.
   c) 32,8 mg of hydrochloric acid (HCl) added to 12,76 $cm^3$ of water.
   d) 1,12 $dm^3$ of a 6,54 $mol.dm^{-3}$ concentration solution of ammonia ($NH_3$) added to 0,50 $dm^3$ of water.
4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1a. 27WB 1b. 27WC 2. 27WD 3a. 27WF 3b. 27WG 3c. 27WH 3d. 27WJ

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## $K_a$ and $K_b$ ESCP7

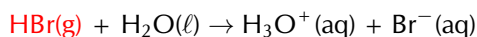
The equilibrium constant for the ionisation process of an acid (the extent to which ions are formed in solution) is given by the term $K_a$, while that for a base is given by $K_b$. These equilibrium constants are a way of determining whether the acid or base is weak or strong.

Remember from Chapter 8 that we calculate K as follows: $K = \frac{[\text{products}]}{[\text{reactants}]}$

**Acids**

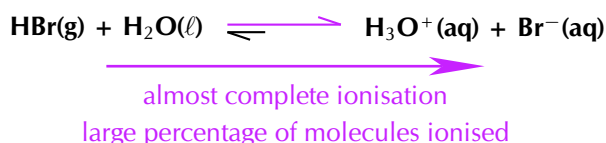
- **Strong acids**

  Consider the ionisation of HBr:

  $HBr(g) + H_2O(\ell) \rightarrow H_3O^+(aq) + Br^-(aq)$

  We are calculating $K_a$ here as it is an acid being dissolved in water. The *liquid* water is not included in the equation.

  $$K_a = \frac{[H_3O^+(aq)][Br^-(aq)]}{[HBr(g)]}$$

  The value of $K_a$ for this reaction is very high (approximately $1 \times 10^9$). This means that there are many more moles of product than reactant. The HBr molecules are almost all ionised to $H^+$ and $Br^-$.

  We can then show that in the ionisation reaction HBr is almost completely ionised. Effectively, any value above $1 \times 10^3$ is large and shows that almost complete ionisation has occurred:

  $$\mathbf{HBr(g) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + Br^-(aq)}$$

  almost complete ionisation

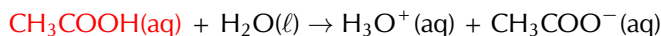
  large percentage of molecules ionised

  The unequal double arrows in the reaction equation indicate that the equilibrium position favours the formation of ions. This is in contrast to the ionisation of a weak acid.

**FACT**
There are really only six strong inorganic acids, the rest are considered weak. These are $HClO_4$ (perchloric acid), HI (hydroiodic acid), HBr (hydrobromic acid), HCl (hydrochloric acid), $H_2SO_4$ (sulfuric acid) and $HNO_3$ (nitric acid).

- **Weak acids**

  Consider the ionisation of ethanoic acid ($CH_3COOH$):

  $CH_3COOH(aq) + H_2O(\ell) \rightarrow H_3O^+(aq) + CH_3COO^-(aq)$

$$K_a = \frac{[H_3O^+(aq)][CH_3COO^-(aq)]}{[CH_3COOH(aq)]}$$

  The value of $K_a$ for this reaction is very low (approximately $1{,}7 \times 10^{-5}$), showing that only a few of the $CH_3COOH$ molecules ionise to form $H_3O^+$ (in water) and $CH_3COO^-$.

  We can write the reaction with an unequal double arrow to show the position of the equilibrium, which does not favour the formation of ions:

$$\mathbf{CH_3COOH(aq) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + CH_3COO^-(aq)}$$

very little ionisation
small percentage of molecules ionised

| Name | Formula | $K_a$ values | Type |
|---|---|---|---|
| Hydrobromic acid | HBr | $1{,}0 \times 10^9$ | strong acid |
| Hydrochloric acid | HCl | $1{,}3 \times 10^6$ | strong acid |
| Sulfuric acid | $H_2SO_4$ | **First** $H^+$: $1{,}0 \times 10^3$ **Second** $H^+$: $1{,}0 \times 10^{-2}$ | strong acid |
| Oxalic acid | $H_2C_2O_4$ | **First** $H^+$: $5{,}8 \times 10^{-2}$ **Second** $H^+$: $6{,}5 \times 10^{-5}$ | weak acid |
| Sulfurous acid | $H_2SO_3$ | **First** $H^+$: $1{,}4 \times 10^{-2}$ **Second** $H^+$: $6{,}3 \times 10^{-8}$ | weak acid |
| Hydrofluoric acid | HF | $3{,}5 \times 10^{-4}$ | weak acid |
| Ethanoic acid | $CH_3COOH$ | $1{,}7 \times 10^{-5}$ | weak acid |

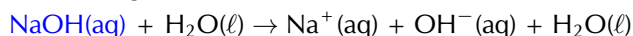
Table 9.5: $K_a$ values for the ionisation of some common acids. Note that sulfuric, oxalic and sulfurous acid can all lose 2 $H^+$ ions (they are diprotic acids).

**Bases**

The dissociation of bases is similar to that of acids in that we look at the $K_b$ values in a similar manner:

- **Strong bases**

  For a strong base like NaOH:

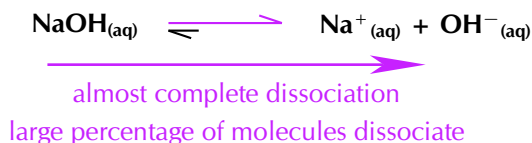
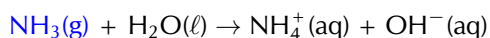
  $NaOH(aq) + H_2O(\ell) \rightarrow Na^+(aq) + OH^-(aq) + H_2O(\ell)$

$$K_b = \frac{[Na^+(aq)][OH^-(aq)]}{[NaOH(aq)]}$$

  The $K_b$ for NaOH is very large (NaOH is a strong base and almost completely dissociates) and shows that the equilibrium lies very far to the $OH^-$ side of the reaction. As a result we can write the equilibrium as:

$$\mathbf{NaOH_{(aq)} \rightleftharpoons Na^+{}_{(aq)} + OH^-{}_{(aq)}}$$

almost complete dissociation
large percentage of molecules dissociate

- **Weak bases**

  $NH_3(g) + H_2O(\ell) \rightarrow NH_4^+(aq) + OH^-(aq)$

$$K_b = \frac{[NH_4^+(aq)][OH^-(aq)]}{[NH_3(g)]}$$

The $K_b$ for $NH_3$ is approximately $1,8 \times 10^{-5}$ ($NH_3$ is a weak base) and shows that the equilibrium lies to the $NH_3$ side of the reaction. As a result we can write the equilibrium as:

$$NH_3(g) + H_2O(\ell) \rightleftharpoons NH_4^+(aq) + OH^-(aq)$$

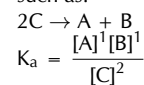
very little ionisation

small percentage of molecules ionised

**TIP**

In a balanced chemical equation such as:

$2C \rightarrow A + B$

$K_a = \frac{[A]^1[B]^1}{[C]^2}$

However, we generally do not include the superscripts when the coefficients in the balanced equation are **1**:

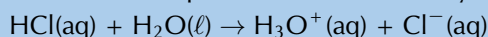
$K_a = \frac{[A][B]}{[C]^2}$

Remember: $x^1 = x$.

### Worked example 6: Equilibrium constant calculations

***QUESTION***

Calculate the equilibrium constant for hydrochloric acid added to 1,38 $dm^3$ of water:

$HCl(aq) + H_2O(\ell) \rightarrow H_3O^+(aq) + Cl^-(aq)$

n(HCl) in solution = 0,005 mol

n($Cl^-$) in solution = 87,3 mol

***SOLUTION***

**Step 1: Calculate the concentration of HCl at equilibrium**

$$C(HCl) = \frac{n}{V} = \frac{0,005 \text{ mol}}{1,38 \text{ dm}^3} = 0,0036 \text{ mol.dm}^{-3}$$

**Step 2: Calculate the concentration of $Cl^-$ at equilibrium**

$$C(Cl^-) = \frac{n}{V} = \frac{87,3 \text{ mol}}{1,38 \text{ dm}^3} = 63,3 \text{ mol.dm}^{-3}$$

**Step 3: Calculate the concentration of $H_3O^+$ at equilibrium**

There is a 1:1 mole ratio between $H_3O^+$ and $Cl^-$. Therefore, if 87,3 mol of $Cl^-$ is present at equilibrium, 87,3 mol of $H_3O^+$ must be present as well.

$$C(H_3O^+) = \frac{n}{V} = \frac{87,3 \text{ mol}}{1,38 \text{ dm}^3} = 63,3 \text{ mol.dm}^{-3}$$

**Step 4: Calculate $K_a$ (because HCl is an acid)**

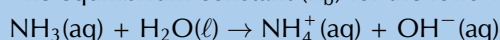
$$K_a = \frac{[H_3O^+(aq)]^1[Cl^-(aq)]^1}{[HCl]^1}$$

$$K_a = \frac{63,3 \times 63,3}{0,0036} = 1,11 \times 10^6$$

### Worked example 7: Equilibrium constant calculations

***QUESTION***

The equilibrium constant ($K_b$) for the following reaction is $1,8 \times 10^{-5}$.

$NH_3(aq) + H_2O(\ell) \rightarrow NH_4^+(aq) + OH^-(aq)$

Calculate the mass (at equilibrium) of $NH_3$ molecules dissolved in 4 $dm^3$ of water if there is a 0,00175 $mol.dm^{-3}$ concentration of hydroxide ions at equilibrium.

### *SOLUTION*

**Step 1: What is the $K_b$ equation for this reaction**

$$K_b = \frac{[NH_4^+(aq)]^1[OH^-(aq)]^1}{[NH_3(aq)]^1}$$

**Step 2: Calculate the concentration of $NH_3$ at equilibrium**

If there is a 0,00175 $mol.dm^{-3}$ concentration of $OH^-$ ions at equilibrium there must be an equal concentration of $NH_4^+$ ions.

$$[NH_3(aq)] = \frac{[NH_4^+(aq)]^1[OH^-(aq)]^1}{K_b} = \frac{(0,00175)(0,00175)}{1,8 \times 10^{-5}} = 0,17 \text{ mol.dm}^{-3}$$

**Step 3: Calculate the number of moles of $NH_3$ at equilibrium**

$C\ (mol.dm^{-3}) = \frac{n\ (mol)}{V\ (dm^3)}$, therefore:

$n = C \times V = 0,17 \text{ mol.dm}^{-3} \times 4 \text{ dm}^3 = 0,68 \text{ mol}$

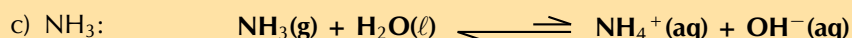
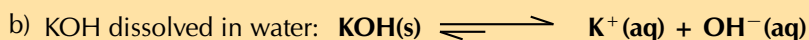
**Step 4: Calculate the mass of $NH_3$ in solution at equilibrium**

$n\ (mol) = \frac{m\ (g)}{M\ (g.mol^{-1})}$. Therefore $m = n \times M$

$M(NH_3) = 14,0 + (3 \times 1,01) = 17,03 \text{ g.mol}^{-1}$

$m = 0,68 \text{ mol} \times 17,03 \text{ g.mol}^{-1} = 11,6 \text{ g}$

**Exercise 9 – 3: Acids and bases**

1. State whether the acids and bases in the following balanced chemical equations are strong or weak and give a reason for your answer.
   a) HF: $\mathbf{HF(g) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + F^-(aq)}$
   b) KOH dissolved in water: $\mathbf{KOH(s) \rightleftharpoons K^+(aq) + OH^-(aq)}$
   c) $NH_3$: $\mathbf{NH_3(g) + H_2O(\ell) \rightleftharpoons NH_4{}^+(aq) + OH^-(aq)}$
   d) HCl $\mathbf{HCl(g) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + Cl^-(aq)}$
2. State whether the acids and bases in the following questions are strong or weak and give a reason for your answer.
   a) $CH_3COOH$ has a $K_a$ value of $1,7 \times 10^{-5}$.
   b) $NH_3$ has a $K_b$ value of $1,8 \times 10^{-5}$.
   c) HI has a $K_a$ value of $3,2 \times 10^9$.
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1a. 27WK 1b. 27WM 1c. 27WN 1d. 27WP 2a. 27WQ 2b. 27WR 2c. 27WS

## 9.2 Acid-base reactions ESCP8

When an acid and a base react, they form a **salt**. If the base contains hydroxide ($OH^-$) ions, then *water* will also be formed. The word *salt* is a general term which applies to the products of all acid-base reactions. A salt is a product that is made up of the **cation** from a **base** and the **anion** from an **acid**.

**FACT**

A **cation** is an ion (charged atom or molecule) with a positive (+) charge. An **anion** is an ion with a negative (-) charge.

**DEFINITION:** *Salt*

A salt is a neutral ionic compound composed of cations and anions. It is the result of an acid-base neutralisation reaction.

**FACT**

Salts are not just the table salt you put on your food. A salt is any compound made up of stoichiometrically equivalent amounts of cations and anions to make a neutral, ionic compound.

### Neutralisation reactions ESCP9

When an equivalent amount of acid and base react (so that neither the acid nor the base are in excess), the reaction is said to have reached the **equivalence** point. At this point **neutralisation** has been achieved.

**DEFINITION:** *Equivalence point*

When a stoichiometrically equivalent number of moles of both reactants has been added to the reaction vessel.

To better understand stoichiometric equivalence look at the following equations:

1. $1HA(aq) + 1BOH(aq) \rightarrow 1AB(aq) + 1H_2O(\ell)$
2. $1H_2A(aq) + 2BOH(aq) \rightarrow 1AB_2(aq) + 2H_2O(\ell)$

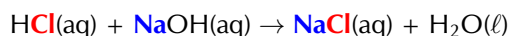
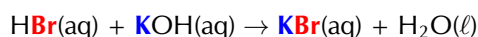
In the first example above, a stoichiometrically equivalent number of moles is **one** mole of HA for every **one** mole of BOH. In the second example, a stoichiometrically equivalent number of moles is **one** mole of $H_2A$ for every **two** moles of BOH.

Magnesium sulfate heptahydrate ($MgSO_4.7H_2O$), commonly known as Epsom salt, can be used as a gel to treat aches and pains, as bath salts, and has many other uses.

**DEFINITION:** *Neutralisation*

A neutralisation reaction involves an acid and a base reacting to form a salt.

Look at the following examples:

- **Hydrochloric acid with sodium hydroxide**
  Hydrochloric acid reacts with sodium hydroxide to form sodium chloride (the salt) and water. Sodium chloride is made up of $Na^+$ cations from the base (NaOH) and $Cl^-$ anions from the acid (HCl).
  $HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(\ell)$
- **Hydrogen bromide with postassium hydroxide**
  Hydrogen bromide reacts with potassium hydroxide to form potassium bromide (the salt) and water. Potassium bromide is made up of $K^+$ cations from the base (KOH) and $Br^-$ anions from the acid (HBr).
  $HBr(aq) + KOH(aq) \rightarrow KBr(aq) + H_2O(\ell)$
- **Hydrochloric acid with sodium hydrocarbonate**
  Hydrochloric acid reacts with sodium hydrocarbonate to form sodium chloride (the salt), water and carbon dioxide. Sodium chloride is made up of $Na^+$ cations from the base ($NaHCO_3$) and $Cl^-$ anions from the acid (HCl).
  $HCl(aq) + NaHCO_3(aq) \rightarrow NaCl(aq) + H_2O(\ell) + CO_2(g)$

**FACT**
Salts can come in many different colours.

Potassium permanganate ($KMnO_4$)

Copper sulfate ($CuSO_4$)

Nickel chloride ($NiCl_2$)

Sodium chromate ($Na_2CrO_4$)

Potassim dichromate ($K_2Cr_2O_7$)

You should notice that in the first two examples, the base contained $OH^-$ ions, and therefore the products were a *salt* and *water*. NaCl (table salt) and KBr are both salts. In the third example, $NaHCO_3$ also acts as a base, despite not having $OH^-$ ions. A salt is still formed as one of the products, but carbon dioxide ($CO_2$) is produced as well as water.

**Informal experiment: Temperature changes in neutralisation reactions**

**Aim:**
To investigate the temperature change associated with a neutralisation reaction.

**Apparatus:**

- 1 $mol.dm^{-3}$ solution of sodium hydroxide (NaOH), 1 $mol.dm^{-3}$ solution of hydrochloric acid (HCl)
- A thermometer, a beaker, a measuring cylinder

**Method:**
**WARNING!**

---

**Concentrated acids and bases can cause serious burns. We suggest using gloves and safety glasses whenever you work with an acid or a base. Remember to add the acid to the water and to avoid sniffing any laboratory chemical. Handle all chemicals with care.**

---

1. Pour 20 $cm^3$ of the sodium hydroxide solution into the beaker.
2. Measure the temperature.
3. Add 5 $cm^3$ of hydrochloric acid to the beaker using the measuring cylinder.
4. Repeat steps 2 and 3 quite quickly until the temperature no longer changes significantly.

**Observations:**

You should record your temperatures and the volume in a table (remember that the volume of the sodium hydroxide is constant at 20 $cm^3$):

| Volume (HCl) | Temperature (°C) |
|---|---|
| 0 | room temperature |
| | |
| | |
| | |

**Discussion:**
You should find that the reaction releases heat and so the temperature increases. After all the base has been neutralised the temperature should no longer increase. This is because the neutralisation reaction is *exothermic* (it releases heat). When all the base has been neutralised there is no reaction on the addition of more acid, and no more heat is released.

Neutralisation reactions are very important in every day life. Below are some examples:

- **Domestic uses**
  Calcium oxide (CaO) is used to neutralise acidic soil. Powdered limestone ($CaCO_3$) can also be used, but its action is much slower and less effective. These substances can also be used on a larger scale in farming and in rivers.
- **Biological uses**
  Hydrochloric acid (HCl) in the stomach plays an important role in helping to digest food. It is important to note that too much acid in the stomach may lead to the formation of ulcers in cases where the stomach lining is damaged (e.g. by an infection).

**Antacids** (which are bases) are taken to neutralise excess stomach acid, to prevent damage to the intestines. Examples of antacids are aluminium hydroxide, magnesium hydroxide ('milk of magnesia') and sodium bicarbonate ('bicarbonate of soda').

- **Industrial uses**

  Alkaline calcium hydroxide (limewater) is used to absorb harmful acidic $SO_2$ gas that is released from power stations and from the burning of fossil fuels.

**WARNING!**

---

**Please do not use a base to neutralise an acid if you spill some on yourself during an experiment. A strong base can burn you as much as a strong acid. Rather wash the area thoroughly with water.**

---

**FACT**

Bee stings are acidic and have a pH between 5 and 5,5. They can be soothed by using substances such as calomine lotion, which is a mild alkali based on zinc oxide. Bicarbonate of soda, or soap, can also be used. The alkalis help to neutralise the acidic bee sting and relieve some of the itchiness.

**Activity: Acids and metal compounds**

Research the reactions that occur when an **acid is added** to the following compounds: (Your Grade 11 book will be helpful with this research)

- a metal
- a metal hydroxide
- a metal oxide
- a metal carbonate
- a metal hydrogen carbonate

Write a report which includes:

- The general equation (in words) of each reaction.
- A description of what is happening in this reaction.
- An example of this type of reaction in the form of a balanced equation.

**Activity: The hazardous nature of acids and bases**

Search for information about the following strong acids and bases:

- Hydrochloric acid (HCl)
- Sulfuric acid ($H_2SO_4$)
- Sodium hydroxide (NaOH)
- Potassium hydroxide (KOH)

Write a report which includes:

- The uses of these compounds in industry
- If applicable, the environmental waste that contains these compounds
- What the effect of a large spillage of these compounds would be

**Worked example 8: Determining equations from starting materials**

***QUESTION***

Magnesium carbonate ($MgCO_3$) is dissolved in nitric acid ($HNO_3$). Give the balanced chemical equation for this reaction.

***SOLUTION***

**Step 1: What are the reactants?**

An acid ($HNO_3$) and a metal carbonate ($MgCO_3$).

**Step 2: What will the products be?**

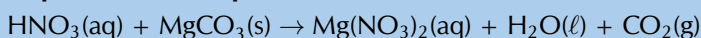
As this is the reaction of an acid and a metal carbonate the products will be a salt, water and carbon dioxide.

nitric acid + magnesium carbonate → salt + water + carbon dioxide

**Step 3: What is the formula of the salt?**

The cation will come from the metal carbonate ($Mg^{2+}$). The anion will come from the acid ($NO_3^-$). Due to the charges on the cation and anion there must be two $NO_3^-$ for every one $Mg^{2+}$.

Therefore the formula for the salt will be: $Mg(NO_3)_2$.

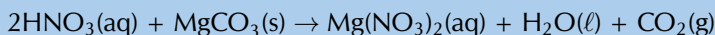
**Step 4: Write the equation for this reaction**

$HNO_3(aq) + MgCO_3(s) \rightarrow Mg(NO_3)_2(aq) + H_2O(\ell) + CO_2(g)$

**Step 5: Make sure that the equation is balanced**

The equation is not balanced.

To balance this equation there needs to be two nitric acid molecules on the left hand side.

| | Number on left | Number on right |
|---|---|---|
| **H** | 1 | 2 |
| **N** | 1 | 2 |
| **O** | 6 | 9 |
| **Mg** | 1 | 1 |
| **C** | 1 | 1 |

$2HNO_3(aq) + MgCO_3(s) \rightarrow Mg(NO_3)_2(aq) + H_2O(\ell) + CO_2(g)$

The equation is now balanced.

| | Number on left | Number on right |
|---|---|---|
| **H** | 2 | 2 |
| **N** | 2 | 2 |
| **O** | 9 | 9 |
| **Mg** | 1 | 1 |
| **C** | 1 | 1 |

**Worked example 9: Determining equations from starting materials**

***QUESTION***

Hydroiodic acid (HI) is added to solid potassium hydroxide (KOH). Give the balanced chemical equation for this reaction.

***SOLUTION***

**Step 1: What are the reactants?**

An acid (HI) and a base (KOH).

**Step 2: What will the products be?**

As this is the reaction of an acid and base (which contains a hydroxide anion) the products will be a salt and water.

hydroiodic acid + potassium hydroxide → salt + water

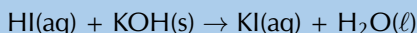
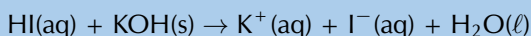
**Step 3: What is the formula of the salt?**

The cation will come from the base ($K^+$). The anion will come from the acid ($I^-$). Due to the charges on the cation and anion there must be one $K^+$ for every one $I^-$. Therefore the formula for the salt will be: KI.

**Step 4: Write the equation for this reaction**

$HI(aq) + KOH(s) \rightarrow KI(aq) + H_2O(\ell)$

This can also be written:

$HI(aq) + KOH(s) \rightarrow K^+(aq) + I^-(aq) + H_2O(\ell)$

**Step 5: Make sure that the equation is balanced**

The equation is balanced.

**Worked example 10: Determining equations from starting materials**

***QUESTION***

Sulfuric acid ($H_2SO_4$) and ammonia ($NH_3$) are combined. Give the balanced chemical equation for this reaction.

***SOLUTION***

**Step 1: What are the reactants?**

An acid ($H_2SO_4$) and a base ($NH_3$).

**Step 2: What will the products be?**

As this is the reaction of an acid and a base (with no hydroxide anion), there will be a salt as a product. There may or may not be another product.

sulfuric acid + ammonia → salt (+ maybe another product)

**Step 3: What is the formula of the salt?**

The cation will come from the base ($NH_4^+$). The anion will come from the acid ($SO_4^{2-}$). Due to the charges on the cation and anion there must be two $NH_4^+$ for every one $SO_4^{2-}$. Therefore the formula for the salt will be: $(NH_4)_2SO_4$.

**Step 4: Write the equation for this reaction so far**

$H_2SO_4(aq) + NH_3(g) \rightarrow (NH_4)_2SO_4(aq)$ (+ maybe another product)

**Step 5: Determine if there will be another product**

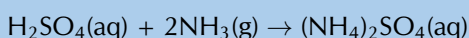
There are no atom types that are not accounted for on both sides of the equation, therefore it is unlikely that there will be another product. If the equation can be balanced then there is no other product.

**Step 6: Make sure that the equation is balanced**

The equation is not balanced.

To balance this equation there needs to be two ammonia molecules on the left hand side.

| | Number on left | Number on right |
|---|---|---|
| **H** | 5 | 8 |
| **S** | 1 | 1 |
| **O** | 4 | 4 |
| **N** | 1 | 2 |

$H_2SO_4(aq) + 2NH_3(g) \rightarrow (NH_4)_2SO_4(aq)$

**FACT**

The term pH was first used by in 1909 by Søren Peter Lauritz Sørensen (a Danish biochemist). The p stood for *potenz* and the H for *hydrogen*. This translates to *power of hydrogen*.

**FACT**

Fizzy cooldrinks often have very low pH (are acidic).

| Drink | pH |
|---|---|
| Coke | 2,5 |
| Diet coke | 3,3 |
| Pepsi | 2,5 |
| Diet pepsi | 3,0 |
| Sprite | 3,2 |
| 7 Up | 3,2 |
| Diet 7 Up | 3,7 |

The equation is now balanced.

| | Number on left | Number on right |
|---|---|---|
| **H** | 8 | 8 |
| **S** | 1 | 1 |
| **O** | 4 | 4 |
| **N** | 2 | 2 |

**Exercise 9 – 4: Reactions of acids and bases**

1. Write balanced equations for these acid and metal reactions:
   a) Hydrochloric acid and calcium
   b) Nitric acid and magnesium
2. Write balanced equations for these acid and metal hydroxide reactions:
   a) Hydrochloric acid and magnesium hydroxide
   b) Nitric acid and aluminium hydroxide
3. Write balanced equations for these acid and metal oxide reactions:
   a) Hydrochloric acid and aluminium oxide
   b) Sulfuric acid and magnesium oxide
4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27WT 2. 27WV 3. 27WW

## 9.3 pH ESCPB

### The pH scale ESCPC

The concentration of specific ions in solution determines whether the solution is acidic or basic. Acids and bases can be described as substances that either increase or decrease the concentration of hydrogen ($H^+$) or hydronium ($H_3O^+$) ions in a solution. An acid *increases* the hydrogen ion concentration in a solution, while a base *decreases* the hydrogen ion concentration.

**pH** is used to measure the concentration of $H^+$ ions ($[H^+]$) and therefore, whether a substance is acidic or basic (alkaline). Solutions with a pH of less than seven are acidic, while those with a pH greater than seven are basic (alkaline). The pH scale ranges from 0 to 14 and a pH of 7 is considered neutral.

**DEFINITION:** *pH*

pH is a measure of the acidity or alkalinity of a solution.

At the beginning of the chapter we mentioned that we encounter many examples of acids and bases in our day-to-day lives. The pH of solutions of some household acids and bases are given in Table 9.6.

| Molecule | Found in | pH | Type |
|---|---|---|---|
| phosphoric acid | fizzy drinks | 2,15 | acid |
| tartaric acid | wine | 2,95 | acid |
| citric acid | lemon juice | 3,14 | acid |
| acetic acid | vinegar | 4,76 | acid |
| carbonic acid | fizzy drinks | 6,37 | acid |
| ammonia | cleaning products | 11,5 | base |
| ammonium hydroxide | cleaning products | 11,63 | base |
| sodium hydroxide | caustic soda | 13 | base |

Table 9.6: The pH of solutions of acids and bases as found in common household items.

## pH calculations ESCPD

pH can be calculated using the following equation: $pH = -\log[H^+]$

$[H^+]$ and $[H_3O^+]$ can be substituted for one another: $pH = -\log[H_3O^+]$

The brackets in the above equation are used to show **concentration** in $mol.dm^{-3}$.

### Worked example 11: pH calculations

***QUESTION***

Calculate the pH of a solution where the concentration of hydrogen ions is $1 \times 10^{-7}$ $mol.dm^{-3}$.

***SOLUTION***

**Step 1: Determine the concentration of hydrogen ions**

In this example, the concentration has been given: $1 \times 10^{-7}$ $mol.dm^{-3}$

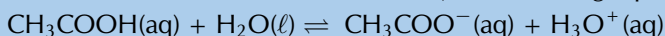
**Step 2: Substitute this value into the pH equation and calculate the pH value**

$pH = -\log[H^+] = -\log(1 \times 10^{-7}) = 7$

### Worked example 12: pH calculations

***QUESTION***

In a 162 $cm^3$ solution of ethanoic acid, the following equilibrium is established:

$CH_3COOH(aq) + H_2O(\ell) \rightleftharpoons CH_3COO^-(aq) + H_3O^+(aq)$

The number of moles of $CH_3COO^-$ is found to be 0,001 mol. Calculate the pH of the solution.

***SOLUTION***

**Step 1: Determine the number of moles of hydronium ions in the solution**

According to the balanced equation for this reaction, the mole ratio of $CH_3COO^-$ ions to $H_3O^+$ ions is 1:1, therefore the number of moles of these two ions in the solution will be the same.

So, $n(H_3O^+) = 0{,}001$ mol.

**Step 2: Determine the concentration of hydronium ions in the solution**

$C\ (mol.dm^{-3}) = \frac{n\ (mol)}{V\ (dm^3)}$

$V = 162\ cm^3 \times \frac{0{,}001\ dm^3}{1\ cm^3} = 0{,}162\ dm^3$

**TIP**

The pH scale is a **log** scale. Remember from mathematics that a difference of one on a base 10 log scale (the one on your calculator) is equivalent to a multiplication by 10. That is:

$1 = \log(10)$

$2 = \log(100)$

$3 = \log(1000)$

$4 = \log(10000)$

So a change from a pH of 2 to a pH of 6 represents a very large change in the $H^+$ concentration.

**TIP**

**Important:** It may be useful to know that for calculations involving the pH scale, the following equations can also be used:

$[H^+][OH^-] = 1 \times 10^{-14}$

$[H_3O^+][OH^-] = 1 \times 10^{-14}$

$pH = 14 - p[OH^-]$

$pH = 14 - (-\log[OH^-])$

**FACT**
A build up of acid in the human body can be very dangerous. **Lactic acidosis** is a condition caused by the buildup of lactic acid in the body. It leads to acidification of the blood (acidosis) and can make a person very ill. Some of the symptoms of lactic acidosis are deep and rapid breathing, vomiting, and abdominal pain. In the fight against HIV, lactic acidosis is a problem. One of the antiretrovirals (ARV's) that is used in anti-HIV treatment is Stavudine (also known as Zerit or d4T). One of the side effects of Stavudine is lactic acidosis, particularly in overweight women. If it is not treated quickly, it can result in death.

**FACT**
Litmus paper can be used as a pH indicator. It is sold in strips. Purple litmus paper will become red in acidic conditions and blue in basic conditions. Blue litmus paper is used to detect acidic conditions, while red litmus paper is used to detect basic conditions.

$$[H_3O^+] = \frac{0{,}001 \text{ mol}}{0{,}162 \text{ dm}^3} = 0{,}0062 \text{ mol.dm}^{-3}$$

**Step 3: Substitute this value into the pH equation and calculate the pH value**

$$\text{pH} = -\log[H^+] = -\log[H_3O^+] = -\log(0{,}0062) = 2.21$$

Understanding pH is very important. In living organisms, it is necessary to maintain a constant pH in the optimal range for that organism, so that chemical reactions can occur.

| **pH** | 1 | 6 | 7 | 8 | 13 |
|---|---|---|---|---|---|
| **$[H^+]$** | $1 \times 10^{-1}$ | $1 \times 10^{-6}$ | $1 \times 10^{-7}$ | $1 \times 10^{-8}$ | $1 \times 10^{-13}$ |
| **$[OH^-]$** | $1 \times 10^{-13}$ | $1 \times 10^{-8}$ | $1 \times 10^{-7}$ | $1 \times 10^{-6}$ | $1 \times 10^{-1}$ |
| **Solution** | **strongly acidic** | weakly acidic | neutral | weakly basic | **strongly basic** |

**acidic solution** **basic solution**

Table 9.7: The concentration of $[H^+]$ and $[OH^-]$ ions in solutions with different pH.

In agriculture, it is important for farmers to know the pH of their soils so that they are able to plant the right kinds of crops. The pH of soils can vary depending on a number of factors, such as rainwater, the kinds of rocks and materials from which the soil was formed and also human influences such as pollution and fertilisers. The pH of rain water can also vary, and this too has an effect on agriculture, buildings, water courses, animals and plants. Rainwater is naturally acidic because carbon dioxide in the atmosphere combines with water to form carbonic acid. Unpolluted rainwater has a pH of approximately 5,6. However, human activities can alter the acidity of rain and this can cause serious problems such as acid rain.

**Exercise 9 – 5: Calculating pH**

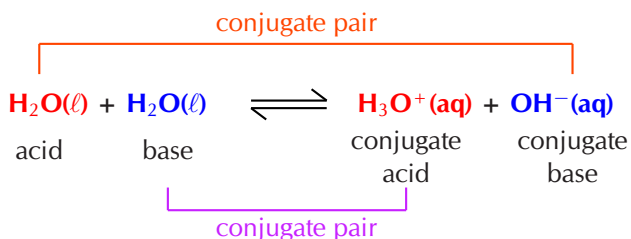
1. Calculate the pH of each of the following solutions:
   (Tip: $[H_3O^+][OH^-] = 1 \times 10^{-14}$ can be used to determine $[H_3O^+]$)
   a) A KOH solution with a 0,2 $\text{mol.dm}^{-3}$ concentration of $OH^-$.
   b) An aqueous solution with a $1{,}83 \times 10^{-7}$ $\text{mol.dm}^{-3}$ concentration of HCl molecules at equilibrium ($K_a = 1{,}3 \times 10^6$)
2. What is the concentration of $H_3O^+$ ions in a solution with a pH of 12?
3. In a typical sample of seawater the concentration the hydronium ($H_3O^+$) ions is $1 \times 10^{-8}$ $\text{mol.dm}^{-3}$, while the concentration of the hydroxide ($OH^-$) ions is $1 \times 10^{-6}$ $\text{mol.dm}^{-3}$.
   a) Is the seawater acidic or basic?
   b) What is the pH of the seawater?
   c) Give a possible explanation for the pH of the seawater.
4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27WX 2. 27WY 3. 27WZ

## $K_w$ ESCPF

Water ionises to a very small extent: $H_2O(\ell) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + OH^-(aq)$

This type of reaction (the transfer of a proton between identical molecules) is known as **auto-protolysis**. This reaction is also known as the **auto-ionisation** of water and the ions formed are a conjugate acid and base pair of water:

**DEFINITION:** *Auto-protolysis and auto-ionisation of water*

Auto-protolysis is the transfer of a proton between two of the same molecules. The auto-ionisation of water is one example of auto-protolysis.

$K_w$ is the equilibrium constant for this process: $K_w = [H_3O^+][OH^-]$

At 25 °C: $[H_3O^+] = [H^+] = 1 \times 10^{-7}$, therefore: $K_w = 1 \times 10^{-14}$ at 25 °C

**TIP**
A neutralisation reaction **does not imply** that the pH is neutral (7).

## Salt hydrolysis ESCPG

Does neutralisation mean that the pH of the solution is 7? No. At the equivalence point of a reaction, the pH of the solution need not be 7. This is because of the interaction of the salt (formed by the reaction) and water.

At the equivalence point of an acid-base neutralisation reaction there is salt and water. The ions of water interact with the salt present and form a small quantity of excess hydronium ions ($H_3O^+$) or hydroxide ions ($OH^-$). This leads to pH values that are not equal to 7.

A simple rule for determining the likely pH of a solution is as follows:

- A **strong** acid + **strong** base form a **neutral** salt and water **solution**:
  $\rightarrow$ pH = 7.
  $H_2SO_4(\ell) + NaOH(s) \rightarrow Na_2SO_4(aq) + H_2O(\ell)$
- A **weak** acid + **strong** base form a **weak basic** salt and water **solution**:
  $\rightarrow$ pH = approximately 9.
  $HF(\ell) + NaOH(s) \rightarrow NaF(aq) + H_2O(\ell)$
- A **strong** acid + **weak** base form a **weak acidic** salt and water **solution**:
  $\rightarrow$ pH = approximately 5.
  $H_2SO_4(\ell) + NH_3(\ell) \rightarrow (NH_4)_2SO_4(aq) + H_2O(\ell)$

| acid | base | solution | approximate pH |
|---|---|---|---|
| strong | strong | neutral | 7 |
| weak | strong | weak basic | 9 |
| strong | weak | weak acidic | 5 |

Table 9.8: The approximate pH of neutralisation reaction solutions based on the strength of the acid and base used.

**FACT**
The universal indicator changes colour from **red** in **strongly acidic** solutions through to **purple** in **strongly basic** solutions.

## Indicators

ESCPH

A titration is a process for determining, with precision, the concentration of a solution with unknown concentration. The theory behind titrations will be discussed later in this chapter. An indicator is used to show the scientist carrying out the reaction exactly when the reaction has reached completion.

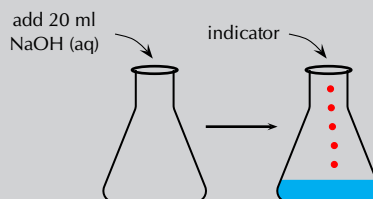
### Experiment: Indicators

**Aim:**
To investigate the use of an indicator in an acid-base reaction.

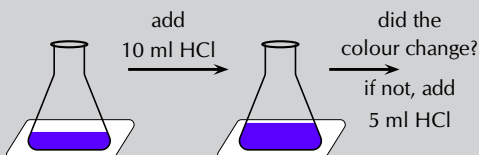
**Apparatus and materials:**

- one volumetric flask, one conical flask, one pipette, a piece of white paper or a white tile
- A 1 mol.dm$^{-3}$ solution of sodium hydroxide (NaOH), a 1 mol.dm$^{-3}$ solution of hydrochloric (HCl), an indicator

**Method:**

1. Measure 20 ml of the sodium hydroxide solution into a conical flask. Add a few drops of the indicator.

2. In this experiment colour change is very important. So place the conical flask on a piece of white paper or a white tile to make any colour change easier to observe.

3. Slowly add 10 ml of hydrochloric acid. If there is a colour change, then stop. If there is no colour change add another 5 ml.

   Continue adding 5 ml increments until you notice a colour change.

**Observations and discussion:**

The solution changes colour after a certain amount of hydrochloric acid is added. This is because the solution now contains more acid than base and has therefore become acidic. It can be concluded that the indicator is one colour in a basic solution and a different colour in an acidic solution.

Indicators are chemical compounds that change colour depending on whether they are in an acidic or a basic solution. A titration requires an indicator that will respond to the change in pH with a sensitive and quick colour change. Typical indicators used in titrations are given in Table 9.9.

| Titration type | Preferred indicator | Colour of acid | Colour of end-point | Colour of base | pH range |
|---|---|---|---|---|---|
| strong acid + strong base | bromothymol blue | yellow | green | blue | 6,0 - 7,6 |
| weak acid + strong base | phenolphthalein | colourless | faint pink | pink | 8,3 - 10,0 |
| strong acid + weak base | bromocresol green | yellow | green | blue | 3,8 - 5,4 |

Table 9.9: Some typical indicators for typcial titrations.

**TIP**
Revise Grade 11 Acids and Bases for more information on plants and foods that can be used as indicators.

**TIP**
Notice that the pH range for colour change of the indicator used should match the approximate pH expected for that type of titration (see Table 9.8):

| solution | pH | pH range |
|---|---|---|
| neutral | 7 | 6,0 - 7,6 |
| weak basic | 9 | 8,3 - 10,0 |
| weak acidic | 5 | 3,8 - 5,4 |

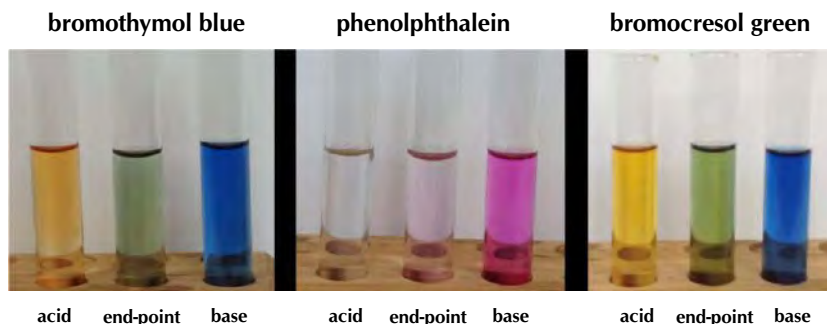
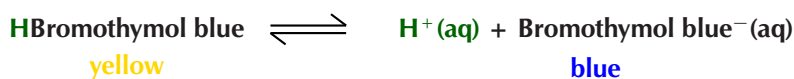



Figure 9.3: Some typical indicators for typcial titrations: bromothymol blue (left), phenolphthalein (centre), and bromocresol green (right).

Indicators change colour (Figure 9.3) according to where the H is:

$$\text{HBromothymol blue} \rightleftharpoons \text{H}^+(\text{aq}) + \text{Bromothymol blue}^-(\text{aq})$$

yellow — blue

So, when an acid is added to aqueous bromothymol blue there will be extra $H^+$ ions. The equilibrium will shift (remember le Chatalier's principle) to decrease the number of $H^+$ ions. That is, to the left. If sufficient acid is added, the entire solution will become acidic. This means there will be more *HBromothymol blue* than *bromothymol blue*$^-$ and the solution will become yellow.

## 9.4 Titrations ESCPJ

### What are titrations? ESCPK

The neutralisation reaction between an acid and a base can be very useful. If an acidic solution of known concentration (a standard solution) is added to a basic (alkaline) solution of unknown concentration until the solution is exactly neutralised (i.e. there is only salt and water), it is possible to calculate the exact concentration of the unknown solution. It is possible to do this because, at the exact point where the solution is neutralised, stoichiometrically equivalent mole amounts of acid and base have reacted with each other.

**DEFINITION:** *Titration*

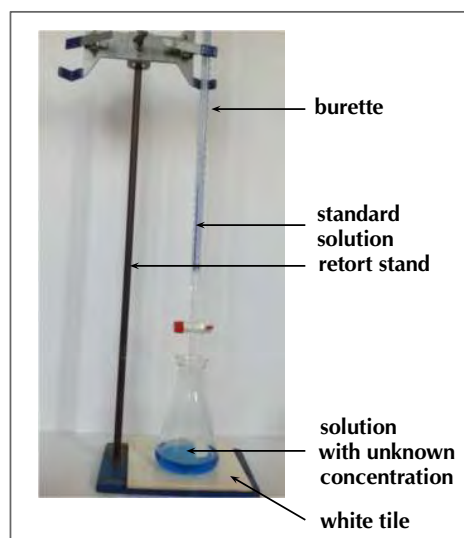
The method used to determine the concentration of a known substance using another, standard, solution.

In a **titration**: a known volume of a standard solution (**A**) is added to a known volume of a solution with unknown concentration (**B**). The concentration of **B** can then be determined.

Acids and bases are commonly used in titrations, and the point of neutralisation is called the **end-point** of the reaction. If you have an indicator that changes colour in the range of the end-point pH then you will be able to see when the end-point has occurred. Another name for a titration is **volumetric analysis**.

## Titration calculations ESCPM

So how exactly can a titration be carried out to determine an unknown concentration? Look at the following steps to help you to understand the process.

1. A carefully measured volume of the solution with unknown concentration is put into a conical flask.
2. A few drops of a suitable indicator is added to this solution (bromothymol blue and phenolphthalein are common indicators, refer to Table 9.9).
3. The conical flask is placed on a white tile or piece of paper (to make colour changes easier to see).
4. A volume of the standard solution (known concentration) is put into a burette (a measuring device) and is slowly added to the solution in the flask, drop by drop.
5. At some point, adding one more drop will change the colour of the unknown solution to the colour of the end-point of the reaction. Remember the colour changes from Figure 9.3.
6. Record the volume of standard solution that has been added up to this point.
7. Use the information you have gathered to calculate the exact concentration of the unknown solution. Worked examples are given to walk you through this step.
8. Note that adding more solution once the end-point has been reached will result in a colour change from the end-point colour to that of the acid (if the solution in the conical flask is a base) or of the base (if the solution in the conical flask is an acid).

When you are busy with these calculations, you will need to remember the following:

$1 \text{ dm}^3 = 1 \text{ litre} = 1000 \text{ ml} = 1000 \text{ cm}^3$, therefore dividing $\text{cm}^3$ by 1000 will give you an answer in $\text{dm}^3$.

Some other terms and equations which will be useful to remember are shown below:

- concentration of a solution is measured in $\text{mol.dm}^{-3}$
- moles (mol) = concentration ($\text{mol.dm}^{-3}$) $\times$ volume ($\text{dm}^3$)
- $\text{concentration} = \frac{\text{moles}}{\text{volume}}$ $\qquad C\ (\text{mol.dm}^{-3}) = \frac{n\ (\text{mol})}{V\ (\text{dm}^3)}$
- remember to make sure all the units are correct in your calculations

### Worked example 13: Titration calculations

***QUESTION***

Given the equation: $NaOH(aq) + HCl(aq) \rightarrow NaCl(aq) + H_2O(\ell)$

25 $cm^3$ of sodium hydroxide solution was pipetted into a conical flask and titrated with 0,2 $mol.dm^{-3}$ hydrochloric acid. Using a suitable indicator, it was found that 15 $cm^3$ of acid was needed to neutralise the base. Calculate the concentration of the sodium hydroxide.

***SOLUTION***

**Step 1: Make sure that the equation is balanced**

There are equal numbers of each type of atom on each side of the equation, so the equation is balanced.

**Step 2: Write down all the information you know about the reaction, converting to the correct units**

**NaOH:** $V = 25\ cm^3 \times \frac{0{,}001\ dm^3}{1\ cm^3} = 0{,}025\ dm^3$

**HCl:** $V = 15\ cm^3 \times \frac{0{,}001\ dm^3}{1\ cm^3} = 0{,}015\ dm^3$ $\quad C = 0{,}2\ mol.dm^{-3}$

**Step 3: Calculate the number of moles of HCl that are added**

$C = \frac{n}{V}$ $\quad$ Therefore, $n(HCl) = C \times V$

$n(HCl) = 0{,}2\ mol.dm^{-3} \times 0{,}015\ dm^3 = 0{,}003\ mol$

0,003 moles of HCl are required to neutralise the base.

**Step 4: Calculate the number of moles of sodium hydroxide in the reaction**

Look at the equation for the reaction: the molar ratio of HCl:NaOH is 1:1.

So for every mole of HCl, there is one mole of NaOH that is involved in the reaction. Therefore, if 0,003 mol HCl is required to neutralise the solution, 0,003 mol NaOH must have been present in the sample of the unknown solution.

**Step 5: Calculate the concentration of the sodium hydroxide solution**

$C(NaOH) = \frac{n}{V} = \frac{0{,}003\ mol}{0{,}025\ dm^3} = 0{,}12\ mol.dm^{-3}$

The concentration of the NaOH solution is 0,12 $mol.dm^{-3}$

### Worked example 14: Titration calculations

***QUESTION***

10 g of solid sodium hydroxide is dissolved in 500 $cm^3$ water. Using titration, it was found that 20 $cm^3$ of this solution was able to completely neutralise 10 $cm^3$ of a sulfuric acid solution. Calculate the concentration of the sulfuric acid.

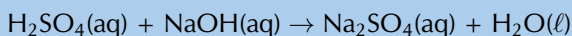
***SOLUTION***

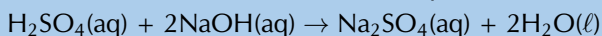
**Step 1: Write a balanced equation for the titration reaction**

The reactants are sodium hydroxide (NaOH) and sulfuric acid ($H_2SO_4$). The base has a hydroxide anion ($OH^-$), therefore the products will be a salt and water.

The cation for the salt ($Na^+$) will come from the base. The anion for the salt ($SO_4^{2-}$) will come from the acid. There must be 2 $Na^+$ cations for every one $SO_4^{2-}$ and the salt

will be $Na_2SO_4$.

$H_2SO_4(aq) + NaOH(aq) \rightarrow Na_2SO_4(aq) + H_2O(\ell)$

To balance the equation we need to multipy the number of sodium hydroxide molecules and the water molecules by two.

$H_2SO_4(aq) + 2NaOH(aq) \rightarrow Na_2SO_4(aq) + 2H_2O(\ell)$

**Step 2: Calculate the concentration of the sodium hydroxide solution**

The total volume that the 10 g was dissolved in must be used to calculate the concentration.

$$V = 500\ cm^3 \times \frac{0,001\ dm^3}{1\ cm^3} = 0,5\ dm^3$$

$$M(NaOH) = 23,0 + 16,0 + 1,01 = 40,01\ g.mol^{-1}$$

$$n(NaOH) = \frac{m}{M} = \frac{10\ g}{40,01\ g.mol^{-1}} = 0,25\ mol$$

$$C(NaOH) = \frac{n}{V} = \frac{0,25\ mol}{0,5\ dm^3} = 0,50\ mol.dm^{-3}$$

**Step 3: Calculate the number of moles of sodium hydroxide that were used in the neutralisation reaction**

Remember that only 20 $cm^3$ of the sodium hydroxide solution is used:

$$V = 20\ cm^3 \times \frac{0,001\ dm^3}{1\ cm^3} = 0,02\ dm^3 \qquad C = \frac{n}{V}, \text{ therefore } n = C \times V$$

$$n = 0,50\ mol.dm^{-3} \times 0,02\ dm^3 = 0,01\ mol$$

**Step 4: Calculate the number of moles of sulfuric acid that were neutralised**

According to the balanced chemical equation, the mole ratio of NaOH to $H_2SO_4$ is 2:1. There are 2 moles of NaOH for every 1 mole of $H_2SO_4$.

$$n(H_2SO_4) = \frac{0,01\ mol}{2} = 0,005\ mol.$$

**Step 5: Calculate the concentration of the sulfuric acid solution**

Remember that 10 $cm^3$ of the sulfuric acid solution is neutralised.

$$V(H_2SO_4) = 10\ cm^3 \times \frac{0,001\ dm^3}{1\ cm^3} = 0,01\ dm^3$$

$$C = \frac{n}{V} = \frac{0,005\ mol}{0,01\ dm^3} = 0,5\ mol.dm^{-3}$$

**Formal experiment: Preparation of a standard solution**

**Aim:**

To prepare a standard solution of sodium hydroxide.

**Apparatus and materials:**

- one 250 $cm^3$ volumetric flask, a beaker, a funnel, a plastic dropper
- A weighing scale, a spatula, a clean piece of paper
- solid sodium hydroxide

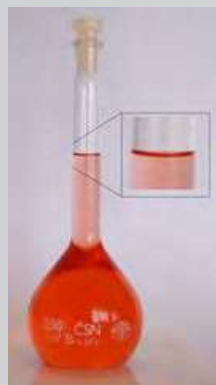
**Method:**

**WARNING!**

---

**Concentrated bases can cause serious burns. We suggest using gloves and safety glasses whenever you work with a base. Handle all chemicals with care.**

---

1. Place the paper on the scale and tare (zero) the scale.
2. Weigh 5,00 g of solid sodium hydroxide onto the paper.
3. Transfer the sodium hydroxide to the beaker and dissolve it in a minimal amount of water.
4. Place the funnel in the mouth of the volumetric flask and use it to transfer the solution from the beaker to the flask, be careful not to spill.
5. Pour another 5 $cm^3$ of water into the beaker, swirl gently, and pour this into the flask through the funnel as well.
6. Repeat step 5 another two times.
7. Pour 5 $cm^3$ of water through the funnel into the flask.
8. Use the plastic dropper to pour water down the inside of the volumetric flask.
9. Fill the volumetric flask to the mark with water. Use the plastic dropper to fill the last few centimeters. Remember to lower yourself so that you are looking directly at the mark when adding the final drops.
10. Cap the flask and shake well. You now have a standard solution.

**Questions:**

- What is the concentration of this standard solution?
- What is the purpose of rinsing the beaker and funnel with water?
- What is the purpose of rinsing the inside of the volumetric flask with water?
- Why do you need to make sure your eyes are level with the mark when adding the final few drops of water?

**Experiment: Titrations**

**Aim:**
To determine the concentration of acetic acid (ethanoic acid) in a sample of vinegar.

**Apparatus and materials:**

- 4 conical flasks, one pipette, one burette, one small funnel, one beaker
- a retort stand, a white piece of paper or a white tile
- the standard NaOH solution prepared in the previous experiment, white vinegar, phenolphthalein

**Method:**

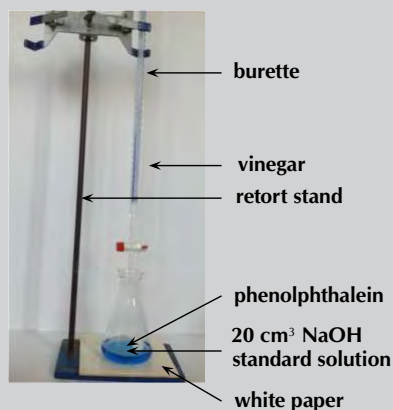
**WARNING!**

**Concentrated acids and bases can cause serious burns. We suggest using gloves and safety glasses whenever you work with an acid or a base. Handle all chemicals with care.**

1. Clamp the burette to the retort stand and place the small funnel on top.
2. Making sure the burette is closed, carefully add the vinegar to the burette (lift the funnel slightly while doing this) until the burette is full.
3. Place a beaker below the burette and carefully let some of the vinegar run into it. This will ensure that there are no air bubbles in the burette. The top of the vinegar should now be between the 0 and 1 $cm^3$ marks. Record the value to the second decimal place.
4. Use your pipette to measure 20 $cm^3$ of the sodium hydroxide standard solution into a conical flask.
5. Add 3 - 4 drops of phenolphthalein indicator to the conical flask. What colour is the solution?
6. Do a rough titration experiment by adding the vinegar to the conical flask quickly, and constantly swirling the conical flask. Stop as soon as the colour of the solution changes, and remains changed after swirling. Make a note of the reading on the burette at this point and determine the volume added:

   (V(final) - V(initial)).

   If the colour change does not remain when the flask is swirled, add more vinegar until the colour remains.

7. Repeat steps 2 - 5 with a second conical flask.
8. Quickly add vinegar to the conical flask until you have added 2 $cm^3$ less than your rough titration volume. There should be no lasting colour change at this point.
9. Drop by drop (slowly and carefully), add vinegar. Swirl between each drop and, if necessary, rinse the sides of the flask with water. When the solution changes colour and remains that new colour, make a note of the volume on the burette.

   Remember that the volume titrated is: (final volume reading) - (the initial volume reading).
10. For accuracy you should repeat steps 7 - 9 until you have three readings with a difference of no more than 0,1 $cm^3$.

**Observations and questions:**

- What colour was the sodium hydroxide solution when the phenolphthalein was added?
- What was the colour when enough acid was added?

Fill in the details of this experiment on a table:

| Titration | Initial volume ($cm^3$) | Final volume ($cm^3$) | Volume ($cm^3$) |
|---|---|---|---|
| Rough | | | |
| 1 | | | |
| 2 | | | |
| 3 | | | |

- From the table determine the average titration volume for this experiment and use that value in the rest of your calculations.
- Using the previous worked examples, determine the concentration of acetic acid in the sample of vinegar. Remember that you have the following information:
  - the volume of vinegar
  - the volume of the sodium hydroxide solution
  - the concentration of the sodium hydroxide solution
- The balanced chemical equation for this reaction is:
  $CH_3COOH(aq) + NaOH(aq) \rightarrow CH_3COONa(aq) + H_2O(\ell)$

**Experiment: Titrations**

**Aim:**

To determine the concentration of a sodium hydroxide solution of unknown concentration.

**Apparatus and materials:**

- one 250 $cm^3$ volumetric flask, 4 conical flasks, one pipette, one burette, one small funnel, two beakers, one plastic dropper
- a retort stand, a weighing scale, a spatula, a clean piece of paper
- solid sodium hydroxide (NaOH), solid oxalic acid ($H_2C_2O_4$), phenolphthalein

**Method:**

**WARNING!**

---

**Concentrated acids and bases can cause serious burns. We suggest using gloves and safety glasses whenever you work with an acid or a base. Handle all chemicals with care.**

---

1. Prepare a standard solution using 11,00 g of oxalic acid in the 250 $cm^3$ volumetric flask.
2. Label one of the beakers *NaOH*. Use your pipette to measure 100 $cm^3$ of water into the beaker. Add approximately 4 g of NaOH to the beaker and stir.
3. Clamp the burette to the retort stand and place the small funnel on top.
4. Making sure the burette is closed, carefully add the oxalic acid standard solution to the burette (lift the funnel slightly while doing this) until the burette is full.
5. Place the clean beaker below the burette and carefully let some of the oxalic acid solution run into it. This will ensure that there are no air bubbles in the burette. The top of the solution should now be between the 0 and 1 $cm^3$ marks. Record the value to the second decimal place.
6. Use your pipette to measure 20 $cm^3$ of the NaOH solution into a conical flask.
7. Add 3 - 4 drops of phenolphthalein indicator to the conical flask. What colour is the solution?

8. Do a rough titration experiment by adding the oxalic acid to the conical flask quickly, and constantly swirling the conical flask. Stop as soon as the colour of the solution changes, and remains changed after swirling. Make a note of the reading on the burette at this point and determine the volume added:

   V(final) - V(initial).

   If the colour change does not remain when the flask is swirled, add more oxalic acid until the colour remains.
9. Repeat steps 4 - 7 with a second conical flask.
10. Quickly add oxalic acid to the conical flask until you have added 2 $cm^3$ less than your rough titration volume. There should be no lasting colour change at this point.
11. Drop by drop (slowly and carefully), add oxalic acid. Swirl between each drop and, if necessary, rinse the sides of the flask with water. When the solution changes colour, and remains that new colour, make a note of the volume on the burette.

    Remember that the volume titrated is: (final volume reading) - (the initial volume reading).
12. For accuracy, you should repeat steps 9 - 11 until you have three readings with a difference of no more than 0,1 $cm^3$.

**Observations and questions:**

- What colour was the sodium hydroxide solution when the phenolphthalein was added?
- What was the colour when enough acid was added?

Fill in the details of this experiment on a table like the one below:

| Titration | Initial volume ($cm^3$) | Final volume ($cm^3$) | Volume ($cm^3$) |
|---|---|---|---|
| **Rough** | | | |
| **1** | | | |
| **2** | | | |
| **3** | | | |

- From the table, determine the average titration volume for this experiment and use that value in the rest of your calculations.
- Using the previous worked examples, determine the concentration of the sodium hydroxide solution. Remember that you have the following information:
  - the volume of sodium hydroxide solution
  - the volume of oxalic acid solution
  - the concentration of the oxalic acid solution.
- The balanced chemical equation for this reaction is:

  $H_2C_2O_4(aq) + 2NaOH(aq) \rightarrow Na_2C_2O_4(aq) + 2H_2O(\ell)$

**Exercise 9 – 6: Acids and bases**

1. A learner is asked to prepare a *standard solution* of the weak acid, oxalic acid ($H_2C_2O_4$), for use in a titration. The volume of the solution must be 500 $cm^3$ and the concentration must be 0,2 $mol.dm^{-3}$.

   a) Calculate the mass of oxalic acid which the learner must dissolve to make up the required standard solution.

b) The learner titrates this 0,2 $mol.dm^{-3}$ oxalic acid solution against a solution of sodium hydroxide. He finds that 40 $cm^3$ of the oxalic acid solution completely neutralises 35 $cm^3$ of the sodium hydroxide solution.
Calculate the concentration of the sodium hydroxide solution.

2. 25,0 $cm^3$ of a 0,1 $mol.dm^{-3}$ standard solution of sodium carbonate was used to neutralise 35,0 $cm^3$ of a solution of hydrochloric acid.
   a) Write a balanced chemical equation for the reaction.
   b) Calculate the concentration of the acid.
   (DoE Grade 11 Exemplar, 2007)
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27X2 2. 27X3

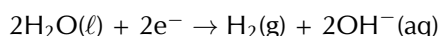
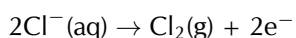
 www.everythingscience.co.za 

## 9.5 Applications of acids and bases ESCPN

### The production of chlorine ESCPP

The chlorine-alkali (chloralkali) industry is an important part of the chemical industry for the production of **chlorine** and **sodium hydroxide**. The most common method involves the electrolysis of a concentrated aqueous solution of sodium chloride (NaCl), which is known as **brine**. For more information on electrolysis see Chapter 13.

The chemical reactions that take place in this process are:

$2Cl^-(aq) \rightarrow Cl_2(g) + 2e^-$ $2H_2O(\ell) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$

There are also $Na^+$ ions from the NaCl in the solution. If the products are kept separate (to prevent a reaction between the chlorine and hydroxide) the $Na^+$ will react with the hydroxide ions making the overall reaction as follows:

$2NaCl(aq) + 2H_2O(\ell) \rightarrow Cl_2(g) + H_2(g) + 2NaOH(aq)$

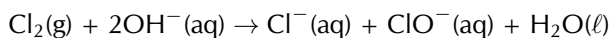
**The uses of chlorine include:**

- the purification of water
- as a disinfectant
- in the production of:
  - hypochlorous acid (used to kill bacteria in drinking water), chloroform, carbon tetrachloride
  - paper, food
  - antiseptics, insecticides, medicines, textiles
  - paints, petroleum products, solvents, plastics (such as polyvinyl chloride)

**The uses of sodium hydroxide include:**

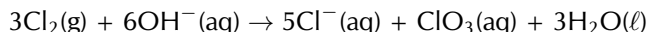
- making soap and other cleaning agents
- purification of bauxite (the ore of aluminium)
- making paper
- making rayon (artificial silk)

If the chlorine and hydroxide ions are not kept separate (i.e. are allowed to react), and the temperature is kept below 60 °C, then the following occurs:

$Cl_2(g) + 2OH^-(aq) \rightarrow Cl^-(aq) + ClO^-(aq) + H_2O(\ell)$

The balanced chemical equation with the inclusion of the $Na^+$ ions is:

$Cl_2(g) + 2NaOH(aq) \rightarrow NaCl(aq) + NaClO(aq) + H_2O(\ell)$

If the temperature is above 60 °C and mixing occurs, then:

$3Cl_2(g) + 6OH^-(aq) \rightarrow 5Cl^-(aq) + ClO_3(aq) + 3H_2O(\ell)$

And the balanced chemical equation including $Na^+$ ions is:

$3Cl_2(g) + 6NaOH(aq) \rightarrow 5NaCl(aq) + NaClO_3(aq) + 3H_2O(\ell)$

**The uses of NaClO (sodium hypochlorite) include:**

- use in bleaches, disinfectants, and water treatments
- use during root canal surgery and to neutralise nerve agents

**The uses of $NaClO_3$ (sodium chlorate) include:**

- making chlorine dioxide
- use as a herbicide
- generating oxygen in chemical oxygen generators

If calcium chloride was used instead of sodium chloride, then the products would be calcium chloride, calcium hypochlorite and calcium chlorate. Similarly, if potassium chloride was used, the products would be potassium chloride, potassium hypochlorite and potassium chlorate.

## The chemistry of hair and hair products ESCPQ

Hair is primarily made up of a protein called **keratin**. Keratin is a macromolecule and consists largely of the amino acid **cystine** (an organic acid, see Figure 9.4).

Amino acids are composed of an amine group (Figure 9.5 (a)) and a carboxylic acid group (Figure 9.5 (b)) connected by a carbon chain.

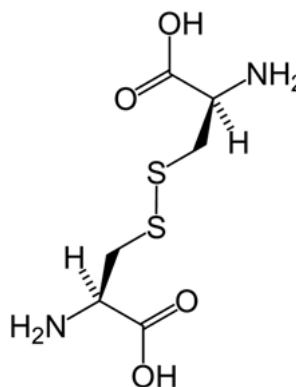



Figure 9.4: The main amino acid found in keratin: **cystine**.

Proteins give hair a natural acidic pH of between 4 and 5. The following hair products alter this pH and do *controlled damage* to get the desired effect.

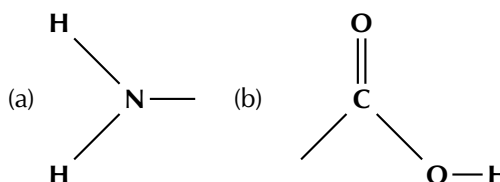
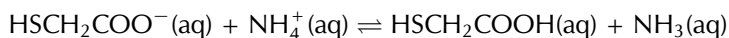



Figure 9.5: **a)** An amine functional group and **b)** a carboxylic acid functional group. Both of these are found in amino acids.

### Permanent waving application

Another name for a permanent waving application is a **perm**. Ammonium thioglycolate is also known as a *perm salt*. The reversible reaction of ammonium thioglycolate (reactant) to form thioglycolic acid and free ammonia (product) is given below:

$$HSCH_2COO^-(aq) + NH_4^+(aq) \rightleftharpoons HSCH_2COOH(aq) + NH_3(aq)$$

There are four common steps in the perming process:

1. The basic ammonia swells the hair and makes it permeable.
2. The thioglycolic acid reduces the sulfur-sulfur bonds in the **cystine** molecules in your hair. This reduces cystine to **cysteine** (Figure 9.6) and allows the hair structure to be changed.

   This reaction occurs faster at higher temperatures, and the hair is generally heated at this time (e.g., on a hot curling iron).

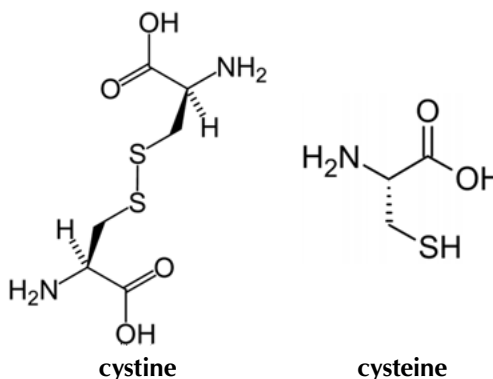



Figure 9.6: **Cystine** (left) is reduced to form **cysteine** (right).

3. The ammonium thioglycolate solution is washed out of the hair after the desired bond breaking has occurred.
4. The hair is treated with hydrogen peroxide ($H_2O_2$), which acts as a neutraliser. It oxidises the cysteine back to cystine (re-forming the sulfur-sulfur bonds). These bonds will form in the new positions formed during the ammonium thioglycolate application. These bonds then fix the hair in this new structure.

**TIP**

**A strand of hair**

untreated
before ammonia

swollen
after ammonia

**FACT**

It is important to use the neutraliser as well as wash the hair thoroughly after a perm application. Excess exposure to the ammonium thioglycolate can cause scalp irritation, as well as permanent hair damage.

### Hair relaxers

Hair relaxers work by doing *controlled damage* to your hair in much the same way as perms do. They reduce the cystine to cysteine and allow the hair structure to be changed (Figure 9.6).

There are two main types of hair relaxers: **lye** and **no-lye**. The **lye** hair relaxers contain sodium hydroxide (NaOH) and have a very high pH (in the range 12 - 14). These types of hair relaxers break bonds and strip the hair of its natural oils. Often heating is also used and this damages the hair even more.

Due to increasing worry about the damage caused by lye hair relaxers, companies have produced **no-lye** hair relaxers. These still contain basic compounds and are still caustic, but their pH is not as high (pH in the range 9 - 11).

These products either use calcium hydroxide and guanidine carbonate (to form guanidine hydroxide, Figure 9.7) or lithium hydroxide. These are bases and act in a similar manner to sodium hydroxide. Although they are milder on hair than sodium hydroxide, they are still damaging. Another type of no-lye hair relaxer contains ammonium thioglycolate (the perm salt).

**guanidine** **guanidine hydroxide**

Figure 9.7: Guanidine (left) and guanidine hydroxide (right). Guanidine hydroxide is formed from guanidine carbonate and calcium hydroxide.

**FACT**
NaOH is used in drain cleaning products to dissolve hair, as well as in procedures that remove body hair.

**FACT**
Remember that the pH scale goes from 0 - 14.

Some comparisons between lye and no-lye hair relaxers are given in Table 9.10.

| | Lye | No-lye |
|---|---|---|
| **pH** | 12 - 14 | 9 - 11 |
| **Benefits** | quick application time | more gentle on scalp |
| **Problems** | high pH, very damaging to scalp and hair | often left on too long, dries hair due to calcium build up |

Table 9.10: Lye versus no-lye hair relaxers.

**Colouring hair**

There are many different types of hair colourants, ranging from permanent hair dye to temporary hair dye. Each of them works in a slightly different way.

- **Permanent**

  In permanent hair dyes there are three main ingredients: a diamino compound (that means two of the amine groups shown in Figure 9.5 (a)); a coupling agent; and an oxidising agent.

  The oxidising agent is generally hydrogen peroxide ($H_2O_2$). It oxidises the diamino compound to a state where it can bond with the coupling agent. This process also lightens the hair so that the dye will work more effectively. This new compound is then oxidised again to form the final dye.

  Permanent dyes are basic with a pH between 9 and11 (usually ammonia, $NH_3$). The purpose of the base is to open up the hair and allow the small dye molecules to penetrate.

- **Demi-permanent**

  These dyes use ethanolamine or sodium carbonate as a base. These are less harsh bases than ammonia (pH between 8 and 9), and so do not allow the dye to penetrate as far into the hair.

  They still contain a hydrogen peroxide developer that lightens the hair slightly. However, they cannot colour dark hair to a lighter colour. The hair colour will look more natural though, as the natural colour of the hair will affect the final dye. Demi-permanent dyes last a long time (at least 12 washes), but will eventually wash out.

  Demi-permanent hair dyes do not damage the hair as much as permanent dyes.

- **Semi-permanent**

  These dyes contain molecules that are small enough to partially penetrate the hair without the need of a base to open the hair. They last for about 4 - 5 washes and have, at most, very low levels of hydrogen peroxide or ammonia. They will not lighten hair and the final colour depends a lot on the original colour and the porosity of the hair.

- **Temporary**

  These are generally bright dyes. They are composed of large dye molecules, which are unable to penetrate the hair. These large molecules *stick* to the hair and usually can be removed with just one wash. If the hair is already dry or damaged the colour may last longer, as the damaged hair is more open and allows the dye molecules to penetrate.

It is worth noting that some of the possible side-effects of using perming applications, hair relaxers and hair colourants are:

- scalp irritation, skin burns, and permanent scarring
- deep ulcerations, dermatitis, skin drying and cracking
- irreversible baldness, eye damage or blindness
- weak, broken, or damaged hair

**Experiment: The effect of drain cleaner on hair**

**Aim:**

To determine the effect of caustic soda or drain cleaner on hair.

**Apparatus:**

- A pile of hair from your hairbrush
- A drain cleaning product or caustic soda flakes
- A watch glass

**WARNING!**

---

**Be careful when handling any drain cleaning products. They are very basic and can burn your skin. We suggest using gloves and safety glasses as well as protective clothing. Handle all chemicals with care.**

---

**Method:**

1. Collect the hair from your hair brush for a week.
2. Place the hair on a watch glass.
3. If you have a liquid drain cleaning product perform step **a**. If you have caustic soda perform step **b**.
   a) Carefully pour a drain cleaning product onto the pile of hair and observe.
   b) Take the solid caustic soda and put a few flakes onto the hair. Boil some water, pour it carefully over the caustic soda and observe.

**Questions:**

- What is the main ingredient in the drain cleaning product and the caustic soda?
- What happened to the hair when this product was applied to it?
- What is the main ingredient of lye hair relaxers?

**Conclusions:**

You should have observed that the hair disintegrated when the drain cleaner was applied. The main ingredient in these cleaners is also the main ingredient in many hair relaxers, although the concentration is lower in the hair relaxers.

## 9.6 Chapter summary ESCPR

See presentation: 27X4 at www.everythingscience.co.za

- The **Arrhenius** definition of acids and bases defines an acid as a substance that increases the concentration of hydronium ions ($H_3O^+$) in a solution. A base is defined as a substance that increases the concentration of hydroxide ions ($OH^-$) in a solution. However, this definition only applies to aqueous solutions (in water).
- The **Brønsted-Lowry** definition is much broader. An **acid** is a substance that **donates protons** ($H^+$) and a **base** is a substance that **accepts protons**.
- In different reactions, certain substances can act as both an acid and a base. These substances are **amphoteric** substances. **Amphiprotic** substances are amphoteric substances that are Brønsted-Lowry acids and bases. Water is both amphoteric and amphiprotic.
- A **conjugate acid-base pair** refers to two compounds (one reactant and one product) that differ only by a hydrogen ion ($H^+$) and a charge of $+1$.
- A large percentage of molecules in a **strong** acid or base dissociate or ionise to

form ions in solution.

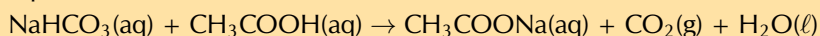
- Only a small percentage of molecules in a **weak** acid or base dissociate or ionise to form ions in solution.
- In a **concentrated** solution there is a **high ratio** of dissolved substance to solvent.
- In a **dilute** solution there is a **low ratio** of dissolved substance to solvent.
- $\mathbf{K_a}$ and $\mathbf{K_b}$ are the equilibrium constants for the reaction of an acid or a base with water. A large $K_a$ or $K_b$ means that the acid or base is **strong**. A small $K_a$ or $K_b$ means that the acid or base is **weak**.
- When an acid and a base react, they form a **salt** and **water**. The salt is made up of a cation from the base and an anion from the acid. An example of a salt is sodium chloride ($NaCl$), which is the product of the reaction between sodium hydroxide ($NaOH$) and hydrochloric acid ($HCl$).
- The reaction between an acid and a base is a **neutralisation** reaction.
- In the reaction between an acid and a **metal** the products are a **salt** and **hydrogen**.
- In the reaction between an acid and a **metal hydroxide** or **metal oxide** the products are a **salt** and **water**.
- In the reaction between an acid and a **metal carbontae** or **metal hydrogen carbonate** the products are a **salt**, **water** and **carbon dioxide**.
- The **pH** scale is a measure of the acidity or alkalinity of a solution. It ranges from 0 to 14. Values greater than 7 indicate a base, while those less than 7 indicate an acid.
- Water ionises to a small extent. $\mathbf{K_w}$ is a measure of this auto-ionisation. $K_w$ is $1 \times 10^{-14}$ at 25 °C.
- An **indicator** is a compound that is a different colour in a basic solution, an acidic solution, and at the end-point of a reaction. They are used to determine the end-point during a neutralisation reaction.
- **Titrations** are the method used to determine the concentration of a known substance using another, standard, solution. Acid-base titrations are an example.
- Two notable applications of acids and bases are in the **chloralkali industry**, and in hair products including **permanent waving applications**, **hair relaxers**, and **hair dyes**.

**Exercise 9 – 7:**

1. The stomach secretes gastric juice, which contains hydrochloric acid. The gastric juice helps with digestion. Sometimes there is an overproduction of acid, leading to heartburn or indigestion. Antacids, such as milk of magnesia, can be taken to neutralise the excess acid. Milk of magnesia is only slightly soluble in water and has the chemical formula $Mg(OH)_2$.
   a) Write a balanced chemical equation to show how the antacid reacts with the acid.
   b) The instructions on the bottle recommend that children under the age of 12 years take one teaspoon of milk of magnesia, whereas adults can take two teaspoons of the antacid. Briefly explain why the dosages are different.
   c) Why is it not advisable to take an overdose of the antacid? Refer to the hydrochloric acid concentration in the stomach in your answer.

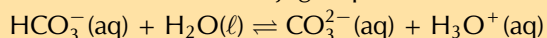
   (DoE Grade 11 Exemplar, 2007)
2. The compound $NaHCO_3$ is commonly known as baking soda. A recipe requires 1,6 g of baking soda, mixed with other ingredients, to bake a cake.
   a) Calculate the number of moles of $NaHCO_3$ used to bake the cake.
   b) How many atoms of oxygen are there in 1,6 g of baking soda?

c) During the baking process, baking soda reacts with an acid (e.g. acetic acid in vinegar) to produce carbon dioxide and water, as shown by the reaction equation below:

$NaHCO_3(aq) + CH_3COOH(aq) \rightarrow CH_3COONa(aq) + CO_2(g) + H_2O(\ell)$

Use the above equation to explain why the cake rises during this baking process.

(DoE Grade 11 Paper 2, 2007)

3. Label the acid-base conjugate pairs in the following equation:

   $HCO_3^-(aq) + H_2O(\ell) \rightleftharpoons CO_3^{2-}(aq) + H_3O^+(aq)$

4. A certain antacid tablet contains 22,0 g of baking soda ($NaHCO_3$). It is used to neutralise the excess hydrochloric acid in the stomach. The balanced equation for the reaction is:

   $NaHCO_3(s) + HCl(aq) \rightarrow NaCl(aq) + H_2O(\ell) + CO_2(g)$

   The hydrochloric acid in the stomach has a concentration of 1,0 $mol.dm^{-3}$. Calculate the volume of the hydrochloric acid that can be neutralised by the antacid tablet.

   (DoE Grade 11 Paper 2, 2007)

5. A learner finds some sulfuric acid solution in a bottle labelled 'dilute sulfuric acid'. He wants to determine the concentration of the sulfuric acid solution. To do this, he decides to titrate the sulfuric acid against a standard potassium hydroxide (KOH) solution.

   a) What is a standard solution?

   b) Calculate the mass of KOH which he must use to make 300 $cm^3$ of a 0,2 $mol.dm^{-3}$ KOH solution.

   c) Calculate the pH of the 0,2 $mol.dm^{-3}$ KOH solution (assume standard temperature).

   d) Write a balanced chemical equation for the reaction between $H_2SO_4$ and KOH.

   e) During the titration the learner finds that 15 $cm^3$ of the KOH solution neutralises 20 $cm^3$ of the $H_2SO_4$ solution. Calculate the concentration of the $H_2SO_4$ solution.

   (IEB Paper 2, 2003)

6. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27X5 2. 27X6 3. 27X7 4. 27X8 5. 27X9

# CHAPTER

# *Electric circuits*

## 10.1 Introduction ESCPS

The study of electrical circuits is essential to understanding the technology that uses electricity in the real-world. In this chapter we will focus on revising content from Grade 11 and extending our understanding of the internal structure of a battery/cell and how this influences what you already know about circuits.

See video: 27XB at www.everythingscience.co.za

**Key linked concepts**

- Units and unit conversions — Physical Sciences, Grade 10, Science skills
- Circuit components — Physical Sciences, Grade 10, Electric circuits
- Ohm's law — Physical Sciences, Grade 11, Electric circuits
- Series and parallel components — Physical Sciences, Grade 11, Electric circuits
- Equations — Mathematics, Grade 10, Equations and inequalities

## 10.2 Series and parallel resistor networks (Revision) ESCPT

In Grade 10 and Grade 11 you learnt about electric circuits and we introduced three quantities which are fundamental to dealing with electric circuits. These quantities are closely related and are **current, voltage (potential difference)** and **resistance**. To recap:

1. Electrical current, $I$, is defined as the rate of flow of charge through a circuit.
2. Potential difference or voltage, $V$, is related to the energy gained or lost per unit charge moving between two points in a circuit. Charge moving through a battery gains energy which is then lost moving through the circuit.
3. Resistance, $R$, is an internal property of a circuit element that opposes the flow of charge. Work must be done for a charge to move through a resistor.

These quantities can be related, in circuit elements whose resistance remains constant, by Ohm's law.

**NOTE:**
**Ohm's Law**
For a resistor at constant temperature the ratio $\frac{V}{I}$ is constant. This ratio we call resistance.
This is equivalent to saying that the amount of electric current through a metal conductor, at a constant temperature, in a circuit is proportional to the voltage across the conductor and can be described by

$$I = \frac{V}{R}$$

In other words, at constant temperature, the resistance of the conductor is constant, independent of the voltage applied across it or current passed through it.

We have focused on the properties of a single component. Now we need to look at a collection of components in a circuit.

**IMPORTANT!**

---

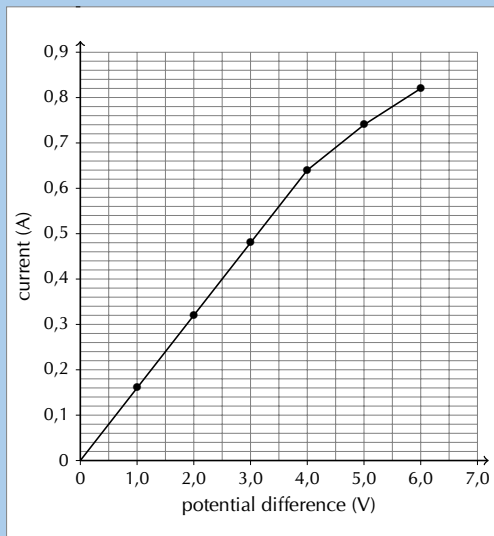
You will often hear people switch between using the terms *voltage* and *potential difference* to describe the same quantity. This is correct but very important to note.

---

Circuits don't consist of a single element and we've learnt about how voltage, current and resistance are affected in circuits with multiple resistors. There are two basic layouts we consider for a network of resistors, series and parallel. Resistors in series and resistors in parallel have different features when talking about current, voltage and equivalent resistance.

**Worked example 1: Ohm's Law [NSC 2011 Paper 1]**

***QUESTION***

Learners conduct an investigation to verify Ohm's law. They measure the current through a conducting wire for different potential differences across its ends. The results obtained are shown in the graph below.

1. Which ONE of the measured quantities is the dependent variable? (1 mark)
2. The graph deviates from Ohm's law at some point.
    a) Write down the coordinates of the plotted point on the graph beyond which Ohm's law is not obeyed.
    (2 marks)
    b) Give a possible reason for the deviation from Ohm's law as shown in the graph. Assume that all measurements are correct.
    (2 marks)
3. Calculate the gradient of the graph for the section where Ohm's law is obeyed.
    Use this to calculate the resistance of the conducting wire.
    (4 marks)

***SOLUTION***

**Question 1:** Current **OR** I (1 mark)

**Question 2:**

The graph deviates from Ohm's law at some point.

1. (4,0 ; 0,64)
   (2 marks)
2. Temperature was not kept constant.
   (2 marks)

**Question 3**

Gradient: $m = \frac{\Delta y}{\Delta x}$

$= \frac{0,64 - 0}{4 - 0}$

$= 0,16$

$R = \frac{1}{0,16}$

$= 6,25\ \Omega$

(4 marks)

**[TOTAL: 9 marks]**

**IMPORTANT!**

A circuit may consist of a combination of parallel and series networks that can in turn be in parallel or series. We can treat parts of the total circuit independently by applying Ohm's Law to each of the components.

**NOTE:**

**Resistors connected in series**

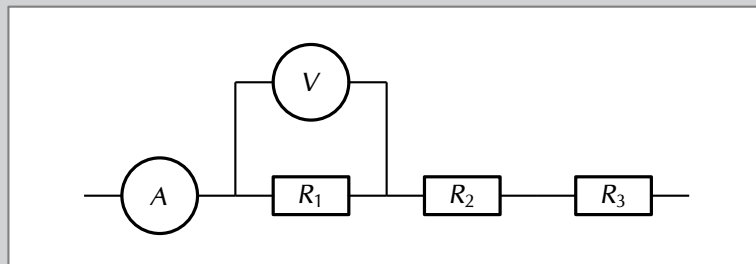
Resistors are in series if they are consecutive elements in the sequence of the circuit and there are no branches between them. For $n$ resistors in series the equivalent resistance is:

$$R_s = R_1 + R_2 + R_3 + \ldots + R_n$$

For $n$ resistors in series the potential difference is split across the resistors:

$$V_{Total} = V_1 + V_2 + V_3 + \ldots + V_n$$

The current is constant through the resistors.

$$I_{Total} = I_1 = I_2 = I_3 = \ldots = I_n$$

It makes sense to remind ourselves of why these are consistent with other topics we have covered previously:

- **Conservation of charge:** we have learnt that charges are not created or destroyed. This is consistent with the current being the same throughout a resistor network

that is in series. Charges aren't being added or lost or bunching up and, therefore, the rate at which charge moves past each point should be the same.

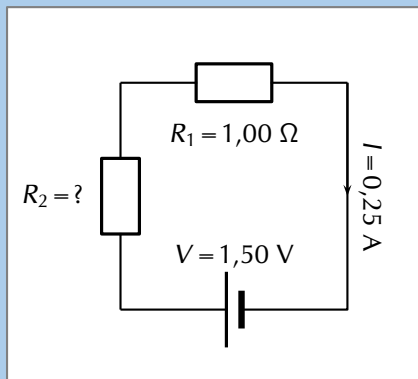
- **Conservation of energy:** we have learnt that energy isn't created or destroyed but transferred through work. The voltage across a resistor is the energy per unit charge (work) required to move through the resistor. The total work done to move through a network of resistors in series should be the sum of the work done to move through each individual resistor.

### Worked example 2: Ohm's Law, all components in series

***QUESTION***

Two ohmic resistors ($R_1$ and $R_2$) are connected in series with a cell with negligible internal resistance. Find the resistance of $R_2$, given that the current flowing through $R_1$ and $R_2$ is 0,25 A and that the potential difference across the cell is 1,50 V. $R_1 = 1{,}00\ \Omega$.

***SOLUTION***

**Step 1: Draw the circuit and fill in all known values.**

**Step 2: Analyse the problem.**

We can use Ohm's Law to find the total resistance R in the circuit, and then calculate the unknown resistance using:

$$R = R_1 + R_2$$

because $R_1$ and $R_2$ are connected in series.

**Step 3: Find the total resistance**

$$\begin{aligned} R &= \frac{V}{I} \\ &= \frac{1{,}5}{0{,}25} \\ &= 6\ \Omega \end{aligned}$$

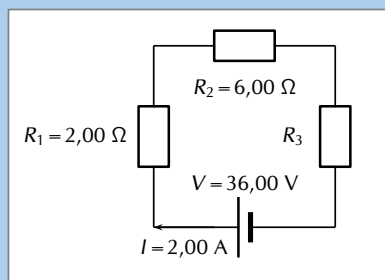
**Step 4: Find the unknown resistance**

We know that $R = 6{,}00\ \Omega$ and that $R_1 = 1{,}00\ \Omega$. Since $R = R_1 + R_2$ and $R_2 = R - R_1$ we know that $R_2 = 5{,}00\ \Omega$.

### Worked example 3: Ohm's Law, series circuit

***QUESTION***

In the case of the circuit shown, calculate:

1. the potential difference of $V_1$, $V_2$ and $V_3$ across the resistors $R_1$, $R_2$, and $R_3$
2. the resistance of $R_3$.

*SOLUTION*

**Step 1: Determine how to approach the problem**

We are given the potential difference across the cell and the current in the circuit, as well as the resistances of two of the three resistors. We can use Ohm's Law to calculate the potential difference across the known resistors. Since the resistors are in a series circuit the potential difference is $V = V_1 + V_2 + V_3$ and we can calculate $V_3$. Now we can use this information to find the potential difference across the unknown resistor $R_3$.

**Step 2: Calculate potential difference across $R_1$**

Using Ohm's Law:

$$\begin{aligned} R_1 &= \frac{V_1}{I} \\ I \cdot R_1 &= I \cdot \frac{V_1}{I} \\ V_1 &= I \cdot R_1 \\ &= 2 \cdot 2 \\ V_1 &= 4{,}00\ \text{V} \end{aligned}$$

**Step 3: Calculate potential difference across $R_2$**

Use Ohm's Law:

$$\begin{aligned} R_2 &= \frac{V_2}{I} \\ I \cdot R_2 &= I \cdot \frac{V_2}{I} \\ V_2 &= I \cdot R_2 \\ &= 2 \cdot 6 \\ V_2 &= 12{,}00\ \text{V} \end{aligned}$$

**Step 4: Calculate potential difference across $R_3$**

Since the potential difference across all the resistors combined must be the same as the potential difference across the cell in a series circuit, we can find $V_3$ using:

$$\begin{aligned} V &= V_1 + V_2 + V_3 \\ V_3 &= V - V_1 - V_2 \\ &= 36 - 4 - 12 \\ V_3 &= 20{,}00\ \text{V} \end{aligned}$$

**Step 5: Find the resistance of $R_3$**

We know the potential difference across $R_3$ and the current through it, so we can use Ohm's Law to calculate the value for the resistance:

$$\begin{aligned} R_3 &= \frac{V_3}{I} \\ &= \frac{20}{2} \\ R_3 &= 10{,}00\ \Omega \end{aligned}$$

**Step 6: Quote the final answer**

- $V_1 = 4{,}00$ V
- $V_2 = 12{,}00$ V
- $V_3 = 20{,}00$ V
- $R_3 = 10{,}00\ \Omega$

**NOTE:**

**Equivalent resistance in a parallel network**

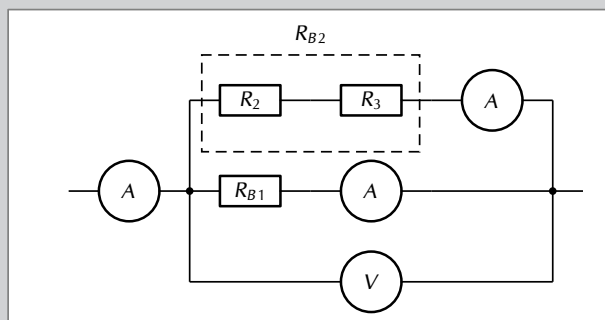
A parallel configuration is when the current splits into a number of branches which contain components (resistors in our case). A branch may contain multiple resistors in series and still be part of the parallel configuration. For $n$ branches of resistors in parallel, the equivalent resistance can be calculated from the total resistance of each branch and is:

$$\frac{1}{R_p} = \frac{1}{R_{B1}} + \frac{1}{R_{B2}} + \frac{1}{R_{B3}} + \ldots + \frac{1}{R_{Bn}}$$

For $n$ branches of resistors in parallel the potential difference is the same across each of the branches:

$$V_{Total} = V_{B1} = V_{B2} = V_{B3} = \ldots = V_{Bn}$$

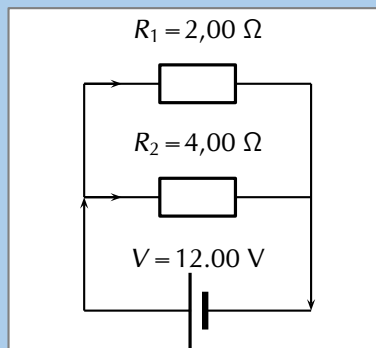
The current is split through the branches.

$$I_{Total} = I_1 + I_2 + I_3 + \ldots + I_n$$

Let's take a moment to see if our conservation laws still make sense:

- **Conservation of charge:** we have learnt that charges are not created or destroyed. This is consistent with the current splitting between the branches. Charges aren't being added or lost or bunching up and, therefore, the total number of charges going through the branches must be the same as the number entering the point where the circuit branches.
- **Conservation of energy:** we have learnt that energy isn't created or destroyed but transferred through work. Energy per unit charge doesn't change unless work is done therefore it makes sense that the energy per unit charge in each branch should be the same.

**Worked example 4: Ohm's Law, resistors connected in parallel**

***QUESTION***

Calculate the current ($I$) in this circuit if the resistors are both ohmic in nature.

***SOLUTION***

**Step 1: Determine what is required**

We are required to calculate the total current flowing in the circuit.

**Step 2: Determine how to approach the problem**

Since the resistors are ohmic in nature, we can use Ohm's Law. However, there are two resistors in the circuit and we need to find the total resistance.

**Step 3: Find the equivalent resistance in the circuit**

Since the resistors are connected in parallel, the total (equivalent) resistance R is:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}.$$

$$\begin{aligned}\frac{1}{R} &= \frac{1}{R_1} + \frac{1}{R_2} \\ &= \frac{1}{2} + \frac{1}{4} \\ &= \frac{2+1}{4} \\ &= \frac{3}{4} \\ \text{Therefore, } R &= \frac{4}{3} = 1{,}33\ \Omega\end{aligned}$$

**Step 4: Apply Ohm's Law**

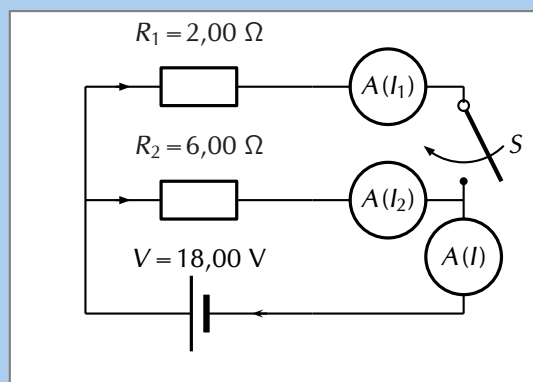
$$\begin{aligned}R &= \frac{V}{I} \\ R \cdot \frac{I}{R} &= \frac{V}{I} \cdot \frac{I}{R} \\ I &= \frac{V}{R} \\ I &= V \cdot \frac{1}{R} \\ &= (12)\left(\frac{3}{4}\right) \\ &= 9{,}00\ \text{A}\end{aligned}$$

**Step 5: Write the final answer**

The total current flowing in the circuit is 9,00 A.

**Worked example 5: Ohm's Law, parallel network of resistors**

***QUESTION***

An 18,00 V cell is connected to two parallel resistors of 2,00 Ω and 6,00 Ω respectively. Calculate the current through each of the ammeters when the switch is closed and when it is open.

***SOLUTION***

**Step 1: Determine how to approach the problem**

We need to determine the current through the cell and each of the parallel resistors. We have been given the potential difference across the cell and the resistances of the resistors, so we can use Ohm's Law to calculate the current.

There are two alternative approaches we could adopt:

- we could use the fact that the potential difference across each of the resistors is the same as the potential difference across the battery because they are in a parallel configuration and then use Ohm's Law; or
- we could determine the equivalent resistance of the circuit and the total current and then use that to determine the current through each of the resistors.

**IMPORTANT!**

Both methods will result in the correct answer if you don't make any calculation errors but one is shorter.

**Step 2: Now determine the current through one of the parallel resistors**

We know that for a configuration with just two resistors in parallel and a cell as in this case, the potential difference across the cell is the same as the potential difference across each of the resistors in parallel. For this circuit:

$$V = V_1 = V_2 = 18{,}00\ \text{V}$$

Let's start with calculating the current through $R_1$ using Ohm's Law:

$$\begin{aligned} R_1 &= \frac{V_1}{I_1} \\ I_1 &= \frac{V_1}{R_1} \\ &= \frac{18{,}00}{2{,}00} \\ I_1 &= 9{,}00\ \text{A} \end{aligned}$$

**Step 3: Calculate the current through the other parallel resistor**

We can use Ohm's Law again to find the current in $R_2$:

$$\begin{aligned} R_2 &= \frac{V_2}{I_2} \\ I_2 &= \frac{V_2}{R_2} \\ &= \frac{18{,}00}{6{,}00} \\ I_2 &= 3{,}00\ \text{A} \end{aligned}$$

**Step 4: Calculate the total current**

The current through each of the parallel resistors must add up to the total current through the cell:

$$\begin{aligned} I &= I_1 + I_2 \\ &= 9{,}00 + 3{,}00 \\ I_2 &= 12{,}00\ \text{A} \end{aligned}$$

**Step 5: When the switch is open**

The branch through $R_1$ is not complete so no current can flow through it. This means we can ignore it completely and consider a simple circuit with a battery and a single resistor, $R_2$, in it.

We can use Ohm's Law again to find the current in $R_2$:

$$
\begin{aligned}
R_2 &= \frac{V_2}{I_2} \\
I_2 &= \frac{V_2}{R_2} \\
&= \frac{18,00}{6,00} \\
I_2 &= 3,00 \text{ A}
\end{aligned}
$$

**Step 6: Write the final answer**

When the switch is closed:

- The current through the cell is 12,00 A.
- The current through the 2,00 Ω resistor is 9,00 A.
- The current through the 6,00 Ω resistor is 3,00 A.

When the switch is open:

- The current through the 6,00 Ω resistor is 3,00 A.

**Informal experiment: Series and parallel networks**

**Aim:**

To investigate the changes in current and voltage when branches of circuits are open or closed..

**Apparatus:**

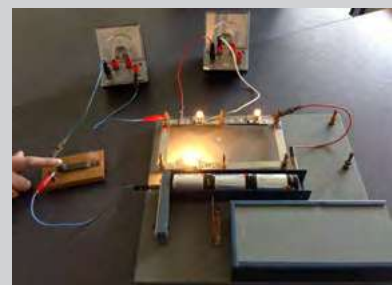
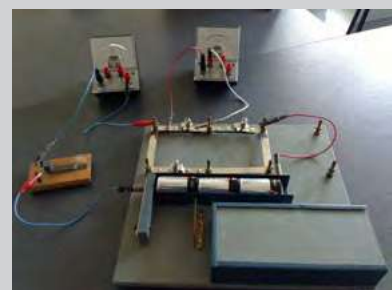
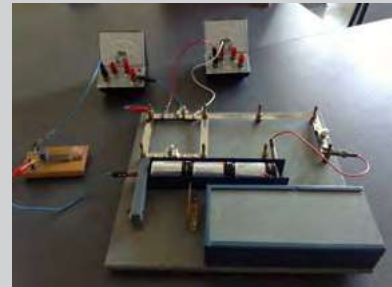
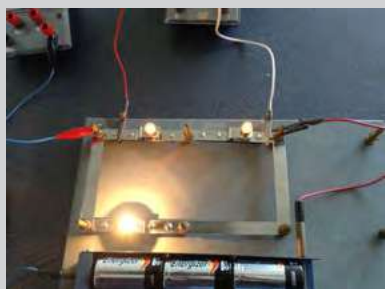
You will need the following items for this investigation:

- batterys / cells
- electric leads
- a set of resistors and/or light bulbs
- ammeters
- voltmeters

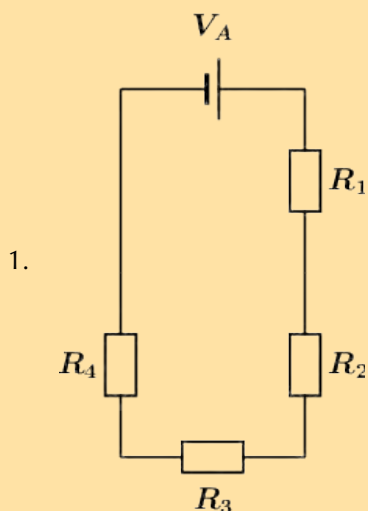
**Method:**

For this investigation, configure a circuit with resistors in both series and in parallel. For example, try:

- including parallel branches with different numbers of light bulbs in each branch
- changing the numbers of light bulbs or resistors in each branch
- try adding a resistor in series with the parallel network

In each branch include an ammeter and a switch. Make notes about what happens when you remove a branch by opening the switch in the branch. What happens to the current in the other branches.

Try to predict what will happen before opening or closing a switch and before adding or removing any light bulbs or resistors.

**Discussion:**
Be sure to note and discuss:

- whether adding a new branch increases or decreases the total current in the circuit,
- whether adding a new branch increases or decreases the current in the original branches,
- whether adding a resistor in series with a parallel network increases or decreases the current, and
- compare what happens when you add a resistor in series with adding another branch to the parallel network.

**Exercise 10 – 1: Series and parallel networks**

1. 


The diagram shows an electric circuit consisting of a battery and four resistors. The **potential difference** (voltage) over the battery is $V_A = 2{,}8$ V
The resistors are rated as follows:

- $R_1 = 7{,}2\ \Omega$
- $R_2 = 4{,}3\ \Omega$
- $R_3 = 7{,}5\ \Omega$
- $R_4 = 4{,}1\ \Omega$

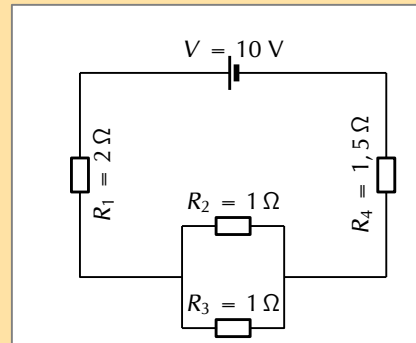
Assume that positive charge is flowing in the circuit (conventional current).
Using the concepts of **Ohm's law**, and **electric circuits**, determine the following:

a) What type of circuit is shown in the diagram?
b) What is the **total equivalent resistance** $R_{eq}$ of the circuit?
   - round your answer to 1 digit after the decimal comma
   - use the values for any physical constants you might need, as listed here: http://www.everythingscience.co.za/physical-constants
c) What is the potential difference (voltage) across $R_1$, or $V_1$ ?
   - round your answer to 3 digits after the decimal comma
   - use the values for any physical constants you might need, as listed here: http://www.everythingscience.co.za/physical-constants
d) What is the potential difference (voltage) across $R_2$, $R_3$, and $R_4$, or $V_2$, $V_3$, and $V_4$?
   - round your answers to 3 digits after the decimal comma

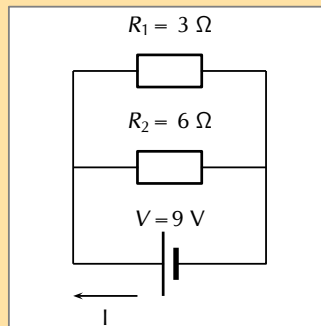
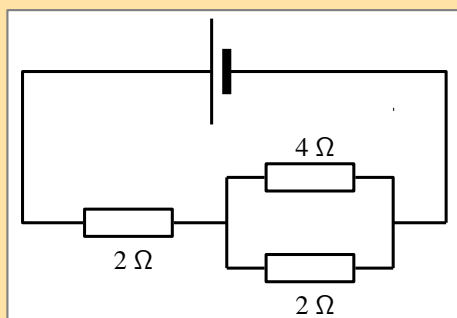
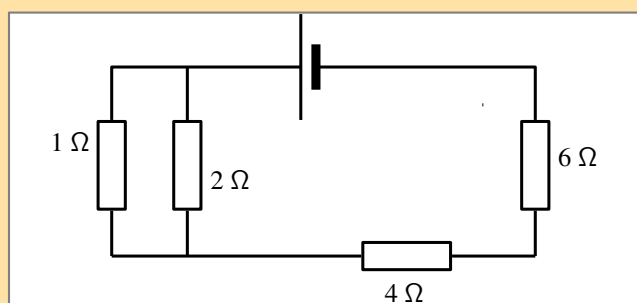
- use the values for any physical constants you might need, as listed here: http://www.everythingscience.co.za/physical-constants

2. For the following circuit, calculate:

   a) the current through the cell
   b) the potential difference across $R_4$
   c) the current through $R_2$

$V = 10$ V
$R_1 = 2\ \Omega$
$R_2 = 1\ \Omega$
$R_3 = 1\ \Omega$
$R_4 = 1,5\ \Omega$

3. Calculate the equivalent resistance of:

   a) three 2 Ω resistors in series;
   b) two 4 Ω resistors in parallel;
   c) a 4 Ω resistor in series with a 8 Ω resistor;
   d) a 6 Ω resistor in series with two resistors (4 Ω and 2 Ω) in parallel.

4. Calculate the total current in this circuit if both resistors are ohmic.

5. Two ohmic resistors are connected in series. The resistance of the one resistor is 4 Ω. What is the resistance of the other resistor if a current of 0,5 A flows through the resistors when they are connected to a voltage supply of 6 V
6. Determine the equivalent resistance of the following circuits:

8. The diagram shows an electric circuit consisting of a battery and four resistors. The **potential difference** (voltage) over the battery is $V_A = 1{,}2$ V The the resistors are rated as follows:

- $R_1 = 4{,}2\ \Omega$
- $R_2 = 2{,}9\ \Omega$
- $R_3 = 3{,}8\ \Omega$
- $R_4 = 3{,}5\ \Omega$

Assume that positive charge is flowing in the circuit (conventional current).

Using the concepts of **Ohm's law**, and **electric circuits**, determine the following:

a) What type of circuit is shown in the diagram?

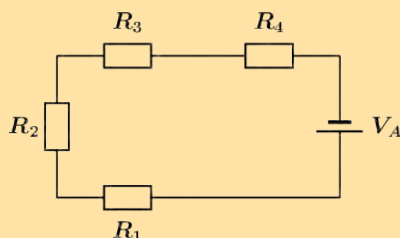
b) What is the **total equivalent resistance** $R_{eq}$ of the circuit?
   - round your answer to 1 digit after the decimal comma
   - use the values for any physical constants you might need, as listed here: http://www.everythingscience.co.za/physical-constants

c) What is the potential difference (voltage) across $R_1$, or $V_1$ ?
   - round your answer to 3 digits after the decimal comma
   - use the values for any physical constants you might need, as listed here: http://www.everythingscience.co.za/physical-constants

d) What is the potential difference (voltage) across $R_2$, $R_3$, and $R_4$, or $V_2$, $V_3$, and $V_4$?
   - round your answers to 3 digits after the decimal comma
   - use the values for any physical constants you might need, as listed here: http://www.everythingscience.co.za/physical-constants

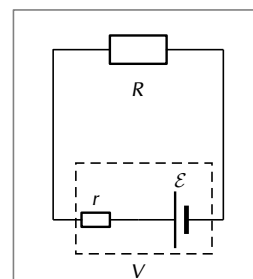
9. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27XC 2. 27XD 3. 27XF 4. 27XG 5. 27XH 6. 27XJ
7. 27XK 8. 27XM

## 10.3 Batteries and internal resistance ESCPV

Up until now we have been dealing with ideal batteries in that they aren't affected by the circuit or current in any way and provide a precise voltage until they go flat.

If you measure the potential difference across the terminals of a battery on its own you will get a different value to what you measure when it is in a complete circuit. The value will be less when the battery is included in a complete circuit. Sometimes the difference is called the *lost volts*. Nothing has actually been lost but energy has been transferred.

Real batteries are made from materials which have resistance. This means that real batteries are not just sources of potential difference (voltage), but they also possess internal resistance. If the total potential difference source is referred to as the emf, $\mathcal{E}$, then a real battery can be represented as an emf connected in series with a resistor $r$. The internal resistance of the battery is represented by the symbol $r$.

**DEFINITION:** *Load*

The external resistance in the circuit is referred to as the load.

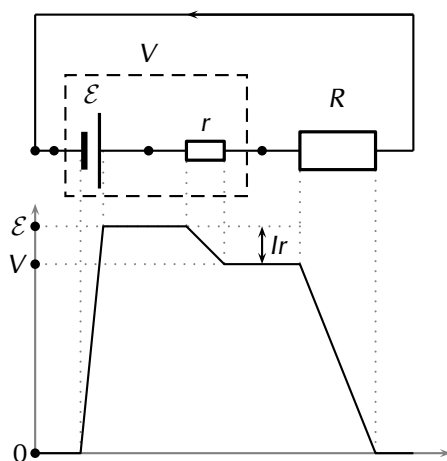
Suppose that the battery with emf $\mathcal{E}$ and internal resistance $r$ supplies a current $I$ through an external load resistor $R$. Then the potential difference across the load resistor is that supplied by the battery: $V_{\text{load}} = I \cdot R$

Similarly, from Ohm's Law, the potential difference across the internal resistance is: $V_{\text{internal resistance}} = I \cdot r$
The potential difference $V$ of the battery is related to its emf $\mathcal{E}$ and internal resistance $r$ by:

$$\mathcal{E} = V + Ir$$

or

$$V = \mathcal{E} - Ir$$

The battery is the source of energy and the energy provided per unit charge (emf) passing through the battery is equal to the total work done (potential difference) across the components in the circuit. This can be illustrated by showing the energy per unit charge as as function of the position in the circuit. The charge gains energy when moving through the battery and loses energy when moving through resistors.

1. Postive work is done on a unit charge by the battery transferring an energy equal to the emf.
2. The charge does work to overcome the internal resistance of the battery. Doing work requires that the charge lose some energy. The work done to overcome the internal resistance is $V_{\text{internal resistance}} = Ir$.
3. When the unit charge leaves the battery it has less energy than the original emf. This is now the total energy that it can use to do work moving through the circuit, $V_{\text{load}} = \mathcal{E} - Ir$.
4. As the charge moves around the circuit it does work passing through each component which is equal to $IR$.

The emf of a battery is essentially constant because it only depends on the chemical reaction (that converts chemical energy into electrical energy) going on inside the battery. Therefore, we can see that the potential difference across the terminals of the battery is dependent on the current drawn by the load. The higher the current, the lower the potential difference across the terminals, because the emf is constant. For the same reason, the potential difference only equals the emf when the current is very small.

The current that can be drawn from a battery is limited by a critical, maximum value $I_c$. The more resistance in the circuit the less the current will be. Imagine that you have a wire with no resistance that you use to connect the terminals of the battery. The circuit is complete, current will flow and adding any resistance to the circuit would decrease the current. The current without any external resistance will be $I_c$. At a current of $I_c$, $V = 0$ V because there is no load in the circuit. Then, the equation becomes:

$$0 = \mathcal{E} - I_c r$$
$$I_c r = \mathcal{E}$$
$$I_c = \frac{\mathcal{E}}{r}$$

The maximum current that can be drawn from a battery is less than $\frac{\mathcal{E}}{r}$.

### Worked example 6: Internal resistance

***QUESTION***

Determine the internal resistance of a battery that has an emf of 12,00 V and has a potential difference across its terminals of 10,00 V when a current of 4,00 A is flowing through the battery when connected in a circuit.

***SOLUTION***

**Step 1: Determine how to approach the problem**
It is an internal resistance problem. So we use the equation:

$$\mathcal{E} = V + Ir$$

**Step 2: Solve the problem**

$$\mathcal{E} = V + Ir$$
$$12 = 10 + 4(r)$$
$$r = 0,5\ \Omega$$

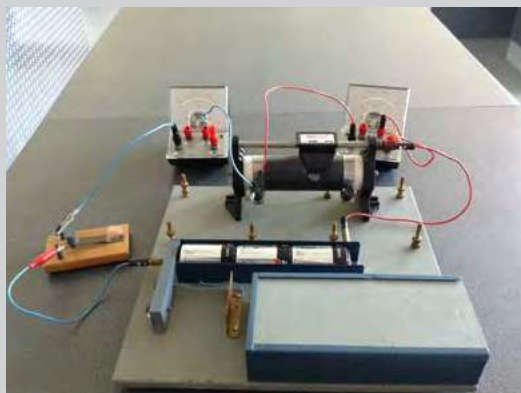
**Step 3: Write the final answer**
The internal resistance of the battery is 0,50 Ω.

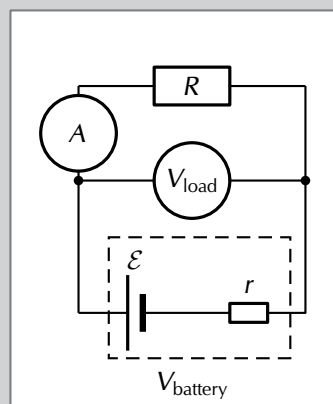
### Formal experiment: Finding the internal resistance of a battery

**Aim:**

To determine the internal resistance of a battery.

**Apparatus:**
You will need the following items for this experiment:

- battery / cell to be studied
- electric leads
- a set of resistors or a rheostat
- ammeter
- voltmeter

**Method:**

We will set up a circuit that contains the battery we want to study in series with a resistor. Then we will measure the potential difference across the load as well as the current for a number of different resistors/rheostat in the circuit. It doesn't matter if it is a different resistor each time or more resistors in series or parallel. What matters is that the overall resistance of the circuit changes so that the current is different each time. The reason that doing this can tell us about the internal resistance of the battery is because the potential difference across the internal resistance is $V_{\text{internal resistance}} = I \cdot r$ and we can vary I by changing the resistance of the circuit.

If the potential difference across the internal resistance is changing and we add up all the potential differences, $\mathcal{E} = V_{\text{load}} + V_{\text{internal resistance}}$ we can determine the internal resistance.

To do this we will actually plot a graph of $V_{\text{load}}$ versus $I$ and then use the features of the graph to determine $\mathcal{E}$ and $r$. To understand why plotting the graph will help us we start with the equation for the magnitude of the $\mathcal{E}$ and substitute Ohm's Law and re-arrange as follows:

$$\begin{aligned}
\mathcal{E} &= V_{\text{load}} + V_{\text{internal resistance}} \\
\mathcal{E} &= V_{\text{load}} + I \cdot r \\
V_{\text{load}} &= \mathcal{E} - I \cdot r \\
V_{\text{load}} &= -r \cdot I + \mathcal{E} \\
\underbrace{V_{\text{load}}}_{y} &= \underbrace{-r}_{m} \cdot \underbrace{I}_{x} + \underbrace{\mathcal{E}}_{c}
\end{aligned}$$

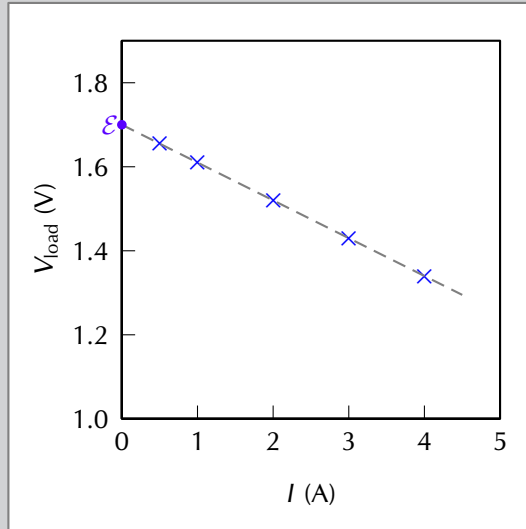
If we plot $V_{\text{load}}$ versus $I$ we will be plotting data that are governed by this relationship. This allows us to conclude that the slope of the graph, $m$, will be $-r$ and the intercept vertical axis, $c$, will be the emf $\mathcal{E}$.

**Results:**

Record your results in a table like the one alongside. You can take more readings if you like.

| **Setup** | $V_{\text{load}}$ (V) | $I$ (A) |
|---|---|---|
| Resistance 1 | | |
| Resistance 2 | | |
| Resistance 3 | | |
| Resistance 4 | | |
| Resistance 5 | | |

**Discussion and conclusion:**

Plot your data on a set of axes similar to this example. The blue crosses represent the measured data points, the gray, dashed line is the drawn straight line through the data points. The best fit line you draw doesn't need to go through all the data points, it should, in general, have as many points above and below the line. The slope of the line can be measured and equated to $-r$ and the intercept with the vertical axis will give you $\mathcal{E}$. The intercept with the horizontal axis would give you the maximum possible current the battery could deliver.

- Do your data form a perfectly straight line?
- What errors were introduced?

**Exercise 10 – 2:**

1. Describe what is meant by the *internal resistance* of a real battery.
2. Explain why there is a difference between the emf and terminal voltage of a battery if the load (external resistance in the circuit) is comparable in size to the battery's internal resistance
3. What is the internal resistance of a battery if its emf is 6 V and the potential difference across its terminals is 5,8 V when a current of 0,5 A flows in the circuit when it is connected across a load?
4. A 12,0 V battery has an internal resistance of 7,0 Ω.
    a) What is the maximum current this battery could supply?
    b) What is the potential difference across its terminals when it is supplying a current of 150.0 mA?
    c) Draw a sketch graph to show how the terminal potential difference varies with the current supplied if the internal resistance remains constant. How could the internal resistance be obtained from the graph?
5. In a hearing aid a battery supplies a current of 25.0 mA through a resistance of 400 Ω. When the volume is increased, the resistance is changed to 100 Ω and the current rises to 60 mA. What is the emf and internal resistance of the cell?
6. A battery is connected in series with a rheostat and an ammeter. When the resistance of the resistor is 10 Ω the current is 2.0 A. When the resistance is 5 Ω the current is 3.8 A. Find the emf and the internal resistance of the battery.
7. When a cell is connected directly across a high resistance voltmeter the reading is 1.50 V. When the cell is shorted through a low resistance ammeter the current

is 2.5 A. What is the emf and internal resistance of the cell?

8. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27XN 2. 27XP 3. 27XQ 4. 27XR 5. 27XS 6. 27XT
7. 27XV

## 10.4 Evaluating internal resistance in circuits ESCPW

### Approach ESCPX

The approach to solving problems that involve the internal resistance of batteries is straightforward, you just need to understand that each battery in previous examples was a source of emf, $\mathcal{E}$, and a small resistor, $r$, and then solve as before but include $r$ in your calculations.

An important thing to realise is that the potential difference you calculated or were given in previous examples is not the emf, it is the emf less that potential difference across the internal resistance.

To emphasise that internal resistance is an extension to what you have already done we are going to take previous worked examples and consider the internal resistance of the battery. If the internal resistance did not behave like an ohmic resistor this wouldn't be possible but we won't deal with cases like that.

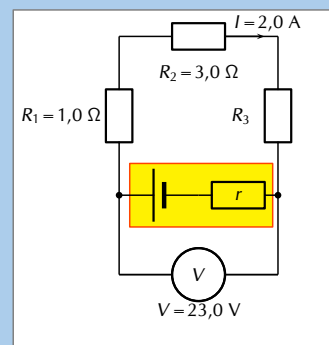
### Applications ESCPY

**Worked example 7: Internal resistance in circuit with resistors in series**

***QUESTION***

For the circuit shown, calculate:

1. the potential differences $V_1$, $V_2$ and $V_3$ across the resistors $R_1$, $R_2$, and $R_3$ .
2. the resistance of $R_3$.
3. the resistance of $R_3$.

If the internal resistance is 0,1 Ω, what is the emf of the battery and what power is dissipated by the internal resistance of the battery?

***SOLUTION***

**Step 1: Note**

This is a very similar question to what you have seen earlier. This is to highlight the fact that the approach when dealing with internal resistance is built on all the same principles you have already been working with.

**Step 2: Determine how to approach the problem**

We are given the potential difference across the cell and the current in the circuit, as well as the resistances of two of the three resistors. We can use Ohm's Law to calculate the potential difference across the known resistors. Since the resistors are in a series circuit the potential difference is $V = V_1 + V_2 + V_3$ and we can calculate $V_3$. Now we can use this information to find the potential difference across the unknown resistor $R_3$.

**Step 3: Calculate potential difference across $R_1$**

Using Ohm's Law:

$$\begin{aligned} R_1 &= \frac{V_1}{I} \\ I \cdot R_1 &= I \cdot \frac{V_1}{I} \\ V_1 &= I \cdot R_1 \\ &= 2 \cdot 1 \\ V_1 &= 2 \text{ V} \end{aligned}$$

**Step 4: Calculate potential difference across $R_2$**

Again using Ohm's Law:

$$\begin{aligned} R_2 &= \frac{V_2}{I} \\ I \cdot R_2 &= I \cdot \frac{V_2}{I} \\ V_2 &= I \cdot R_2 \\ &= 2 \cdot 3 \\ V_2 &= 6 \text{ V} \end{aligned}$$

**Step 5: Calculate potential difference across $R_3$**

Since the potential difference across all the resistors combined must be the same as the potential difference across the cell in a series circuit, we can find $V_3$ using:

$$\begin{aligned} V &= V_1 + V_2 + V_3 \\ V_3 &= V - V_1 - V_2 \\ &= 23 - 2 - 6 \\ V_3 &= 15 \text{ V} \end{aligned}$$

**Step 6: Find the resistance of $R_3$**

We know the potential difference across $R_3$ and the current through it, so we can use Ohm's Law to calculate the value for the resistance:

$$\begin{aligned} R_3 &= \frac{V_3}{I} \\ &= \frac{15}{2} \\ R_3 &= 7{,}5\ \Omega \end{aligned}$$

**Step 7: Potential difference across the internal resistance of the battery**

The value of the emf can be calculated from the potential difference of the load and the potential difference across the internal resistance.

$$\begin{aligned} \mathcal{E} &= V + Ir \\ &= 23 + (2)(0{,}1) \\ &= 23{,}2 \text{ V} \end{aligned}$$

**Step 8: Power dissipated in the battery**

We know that the power dissipated in a resistor is given by $P = VI = I^2R = \frac{V^2}{R}$ and we know the current in the circuit, the internal resistance and the potential difference across it so we can use any form of the equation for power:

$$\begin{aligned} P_r &= V_r I_r \\ &= (0{,}2)(2) \\ &= 0{,}4 \text{ W} \end{aligned}$$

**Step 9: Write the final answer**

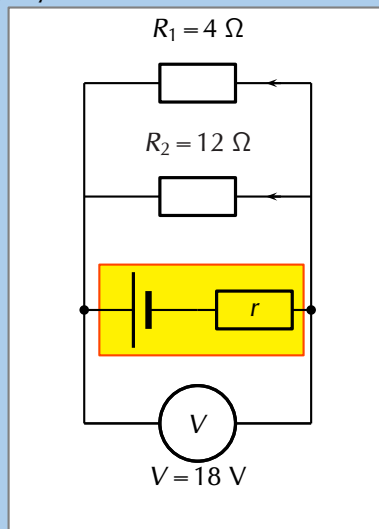
- $V_1 = 2{,}0$ V
- $V_2 = 6{,}0$ V
- $V_3 = 10{,}0$ V
- $R_3 = 7{,}5\Omega$
- $\mathcal{E} = 23{,}2$ V
- $P_r = 0{,}4$ W

**Worked example 8: Internal resistance and resistors in parallel**

***QUESTION***

The potential difference across a battery measures 18 V when it is connected to two parallel resistors of 4,00 Ω and 12,00 Ω respectively. Calculate the current through the cell and through each of the resistors. If the internal resistance of the battery is 0,375 Ω what is the emf of the battery?

***SOLUTION***

**Step 1: First draw the circuit before doing any calculations**

**Step 2: Determine how to approach the problem**

We need to determine the current through the cell and each of the parallel resistors. We have been given the potential difference across the cell and the resistances of the resistors, so we can use Ohm's Law to calculate the current.

**Step 3: Calculate the current through the cell**

To calculate the current through the cell we first need to determine the equivalent resistance of the rest of the circuit. The resistors are in parallel and therefore:

$$\begin{aligned}\frac{1}{R} &= \frac{1}{R_1} + \frac{1}{R_2} \\ &= \frac{1}{4} + \frac{1}{12} \\ &= \frac{3+1}{12} \\ &= \frac{4}{12} \\ R &= \frac{12}{4} = 3{,}00\ \Omega\end{aligned}$$

Now using Ohm's Law to find the current through the cell:

$$R = \frac{V}{I}$$
$$I = \frac{V}{R} = \frac{18}{3}$$
$$I = 6{,}00 \text{ A}$$

**Step 4: Now determine the current through one of the parallel resistors**

We know that for a purely parallel resistor configuration, the potential difference across the cell is the same as the potential difference across each of the parallel resistors. For this circuit:

$$V = V_1 = V_2 = 18 \text{ V}$$

Let's start with calculating the current through $R_1$ using Ohm's Law:

$$R_1 = \frac{V_1}{I_1}$$
$$I_1 = \frac{V_1}{R_1} = \frac{18}{4}$$
$$I_1 = 4{,}50 \text{ A}$$

**Step 5: Calculate the current through the other parallel resistor**

We can use Ohm's Law again to find the current in $R_2$:

$$R_2 = \frac{V_2}{I_2}$$
$$I_2 = \frac{V_2}{R_2} = \frac{18}{12}$$
$$I_2 = 1{,}50 \text{ A}$$

An alternative method of calculating $I_2$ would have been to use the fact that the currents through each of the parallel resistors must add up to the total current through the cell:

$$I = I_1 + I_2$$
$$I_2 = I - I_1 = 6 - 4.5$$
$$I_2 = 1{,}5 \text{ A}$$

**Step 6: Determine the emf**

This total current through the battery is the current through the internal resistance of the battery. Knowing the current and resistance allows us to use Ohm's law to determine the potential difference across the internal resistance and therefore the emf of the battery.
Using Ohm's law we can determine the potential difference across the internal resistance:

$$V = I \cdot r = 6 \cdot 0{,}375 = 2{,}25 \text{ V}$$

We know that the emf of the battery is the potential difference across the terminal summed with the potential difference across the internal resistance so:

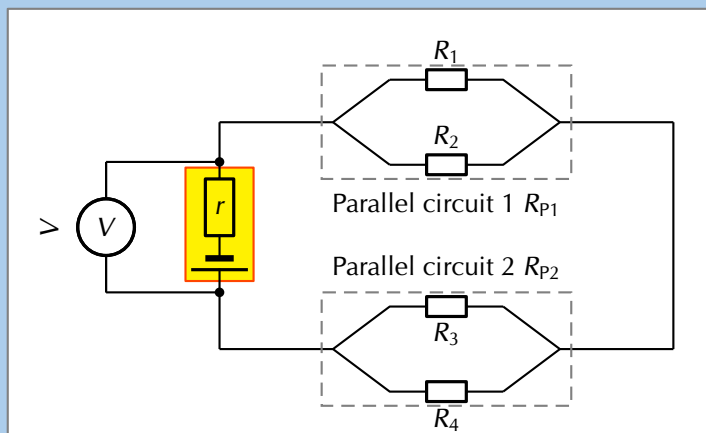
$$\mathcal{E} = V + Ir = 18 + 2{,}25 = 20{,}25 \text{ V}$$

**Step 7: Write the final answer**

The current through the cell is 6,00 A. The current through the 4,00 Ω resistor is 4,50 A. The current through the 12,00 Ω resistor is 1,50 A. The emf of the battery is 20,25 V.

**Worked example 9: Power in series and parallel networks of resistors**

***QUESTION***

Given the following circuit:

The current leaving the battery is 1,07 A, the total power dissipated in the external circuit is 6,42 W, the ratio of the total resistances of the two parallel networks $R_{P1} : R_{P2}$ is 1:2, the ratio $R_1 : R_2$ is 3:5 and $R_3 = 7{,}00\ \Omega$.

Determine the:

1. potential difference of the battery,
2. the power dissipated in $R_{P1}$ and $R_{P2}$, and
3. if the battery is labelled as having an emf of 6,50 V what is the value of the resistance of each resistor and the power dissipated in each of them.

***SOLUTION***

**Step 1: What is required**

In this question you are given various pieces of information and asked to determine the power dissipated in each resistor and each combination of resistors. Notice that the information given is mostly for the overall circuit. This is a clue that you should start with the overall circuit and work downwards to more specific circuit elements.

**Step 2: Calculating the potential difference of the battery**

Firstly we focus on the battery. We are given the power for the overall circuit as well as the current leaving the battery. We know that the potential difference across the terminals of the battery is the potential difference across the circuit as a whole.

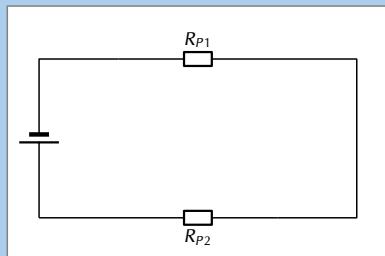
We can use the relationship $P = VI$ for the entire circuit because the potential difference is the same as the potential difference across the terminals of the battery:

$$
\begin{aligned}
P &= VI \\
V &= \frac{P}{I} \\
&= \frac{6{,}42}{1{,}07} \\
&= 6{,}00\ \text{V}
\end{aligned}
$$

The potential difference across the battery is 6,00 V.

**Step 3: Power dissipated in $R_{P1}$ and $R_{P2}$**

Remember that we are working from the overall circuit details down towards those for individual elements, this is opposite to how you treated this circuit earlier.

We can treat the parallel networks like the equivalent resistors so the circuit we are currently dealing with looks like:

We know that the current through the two circuit elements will be the same because it is a series circuit and that the resistance for the total circuit must be: $R_{Ext} = R_{P1} + R_{P2}$. We can determine the total resistance from Ohm's Law for the circuit as a whole:

$$\begin{aligned} V_{battery} &= IR_{Ext} \\ R_{Ext} &= \frac{V_{battery}}{I} \\ &= \frac{6{,}00}{1{,}07} \\ &= 5{,}61\ \Omega \end{aligned}$$

We know that the ratio between $R_{P1} : R_{P2}$ is 1:2 which means that we know:

$$\begin{aligned} R_{P1} &= \frac{1}{2}R_{P2} \text{ and} \\ R_{T} &= R_{P1} + R_{P2} \\ &= \frac{1}{2}R_{P2} + R_{P2} \\ &= \frac{3}{2}R_{P2} \\ (5{,}61) &= \frac{3}{2}R_{P2} \\ R_{P2} &= \frac{2}{3}(5{,}61) \\ R_{P2} &= 3{,}74\ \Omega \end{aligned}$$

and therefore:

$$\begin{aligned} R_{P1} &= \frac{1}{2}R_{P2} \\ &= \frac{1}{2}(3.74) \\ &= 1{,}87\ \Omega \end{aligned}$$

Now that we know the total resistance of each of the parallel networks we can calculate the power dissipated in each:

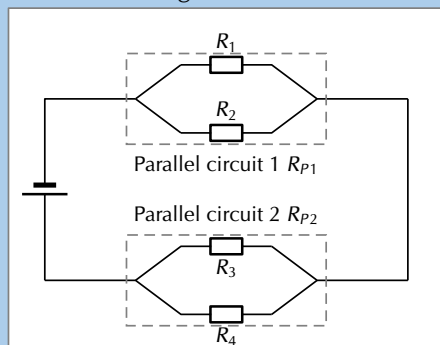
$$\begin{aligned} P_{P1} &= I^2R_{P1} \\ &= (1{,}07)^2(1{,}87) \\ &= 2{,}14\ \text{W} \end{aligned}$$

and

$$\begin{aligned} P_{P2} &= I^2R_{P2} \\ &= (1{,}07)^2(3{,}74) \\ &= 4{,}28\ \text{W} \end{aligned}$$

These values will add up to the original power value we had for the external circuit. If they didn't we would have made a calculation error.

**Step 4: Parallel network 1 calculations**

Now we can begin to do the detailed calculation for the first set of parallel resistors.

We know that the ratio between $R_1 : R_2$ is 3:5 which means that we know $R_1 = \frac{3}{5}R_2$. We also know the total resistance for the two parallel resistors in this network is 1,87 Ω. We can use the relationship between the values of the two resistors as well as the formula for the total resistance ($\frac{1}{R_PT} = \frac{1}{R_1} + \frac{1}{R_2}$) to find the resistor values:

$$\frac{1}{R_{P1}} = \frac{1}{R_1} + \frac{1}{R_2}$$
$$\frac{1}{R_{P1}} = \frac{5}{3R_2} + \frac{1}{R_2}$$
$$\frac{1}{R_{P1}} = \frac{1}{R_2}(\frac{5}{3} + 1)$$
$$\frac{1}{R_{P1}} = \frac{1}{R_2}(\frac{5}{3} + \frac{3}{3})$$
$$\frac{1}{R_{P1}} = \frac{1}{R_2}\frac{8}{3}$$
$$R_2 = R_{P1}\frac{8}{3}$$
$$= (1,87)\frac{8}{3}$$
$$= 4,99\ \Omega$$

We can also calculate $R_1$:

$$R_1 = \frac{3}{5}R_2$$
$$= \frac{3}{5}(4,99)$$
$$= 2,99\ \Omega$$

To determine the power we need the resistance which we have calculated and either the potential difference or current. The two resistors are in parallel so the potential difference across them is the same as well as the same as the potential difference across the parallel network. We can use Ohm's Law to determine the potential difference across the network of parallel resistors as we know the total resistance and we know the current:

$$V = IR$$
$$= (1,07)(1,87)$$
$$= 2,00\ \text{V}$$

We now have the information we need to determine the power through each resistor:

$$P_1 = \frac{V^2}{R_1}$$
$$= \frac{(2,00)^2}{2,99}$$
$$= 1,34\ \text{W}$$

$$P_2 = \frac{V^2}{R_2}$$
$$= \frac{(2,00)^2}{4,99}$$
$$= 0,80\ \text{W}$$

**Step 5: Parallel network 2 calculations**

Now we can begin to do the detailed calculation for the second set of parallel resistors.
We are given $R_3 = 7,00\ \Omega$ and we know $R_{P2}$ so we can calculate $R_4$ from:

$$\frac{1}{R_{P2}} = \frac{1}{R_3} + \frac{1}{R_4}$$
$$\frac{1}{3,74} = \frac{1}{7,00} + \frac{1}{R_4}$$
$$R_4 = 8,03\ \Omega$$

We can calculate the potential difference across the second parallel network by subtracting the potential difference of the first parallel network from the battery potential difference, $V_{P2} = 6,00 - 2,00 = 4,00$ V.

We can now determine the power dissipated in each resistor:

$$P_3 = \frac{V^2}{R_3}$$
$$= \frac{(4,00)^2}{7,00}$$
$$= 2,29\ \text{W}$$

$$P_4 = \frac{V^2}{R_2}$$
$$= \frac{(4,00)^2}{8,03}$$
$$= 1,99\ \text{W}$$

**Step 6: Internal resistance**

We know that the emf of the battery is 6,5 V but that the potential difference measured across the terminals is only 6 V.

The difference is the potential difference across the internal resistance of the battery and we can use the known current and Ohm's law to determine the internal resistance:

$$V = I \cdot R$$
$$R = \frac{V}{I}$$
$$= \frac{0,5}{1,07}$$
$$= 0,4672897$$
$$= 0,47\ \Omega$$

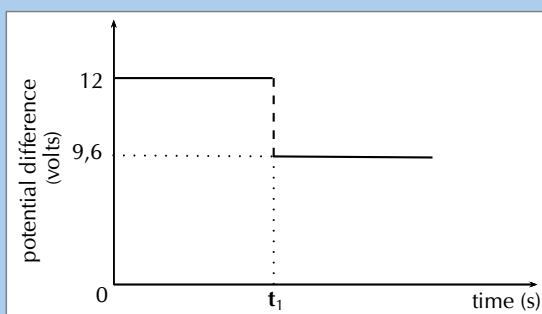
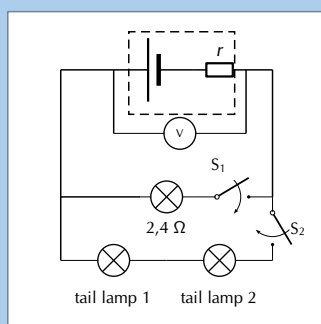
The power dissipated by the internal resistance of the battery is:

$$P = VI$$
$$= 0,5 \cdot 1,07$$
$$= 0,535\ \text{W}$$

**Worked example 10: Internal resistance and headlamps [NSC 2011 Paper 1]**

***QUESTION***

The headlamp and two IDENTICAL tail lamps of a scooter are connected in parallel to a battery with unknown internal resistance as shown in the simplified circuit diagram below. The headlamp has a resistance of 2,4 Ω and is controlled by switch $\mathbf{S_1}$. The tail lamps are controlled by switch $\mathbf{S_2}$. The resistance of the connecting wires may be ignored.

The graph alongside shows the potential difference across the terminals of the battery before and after switch $\mathbf{S_1}$ is closed (whilst switch $\mathbf{S_2}$ is open). Switch $\mathbf{S_1}$ is closed at time $\mathbf{t_1}$.

1. Use the graph to determine the emf of the battery. (1 mark)
2. WITH ONLY SWITCH $\mathbf{S_1}$ CLOSED, calculate the following:
   a) Current through the headlamp (3 marks)
   b) Internal resistance, *r*, of the battery (3 marks)
3. BOTH SWITCHES $\mathbf{S_1}$ AND $\mathbf{S_2}$ ARE NOW CLOSED. The battery delivers a current of 6 A during this period.
   Calculate the resistance of each tail lamp. (5 marks)
4. How will the reading on the voltmeter be affected if the headlamp burns out? (Both switches $\mathbf{S_1}$ and $\mathbf{S_2}$ are still closed.)

Write down only INCREASES, DECREASES or REMAINS THE SAME. Give an explanation. (3 marks)

***SOLUTION***

**Question 1:** 12 V (1 mark)

**Question 2.1**

**Option 1:**

$$I = \frac{V}{R} = \frac{9,6}{2,4} = 4\text{ A}$$

**Option 2:**

$$\text{emf} = IR + Ir$$
$$12 = I(2,4) + 2,4$$
$$\therefore I = 4\text{ A}$$

(3 marks)

**Question 2.2**

**Option 1:**

$$\text{emf} = IR + Ir$$
$$12 = 9,4 + 4r$$
$$r = 0,6\ \Omega$$

**Option 2:**

$$V_{lost} = Ir$$
$$2,4 = 4r$$
$$\therefore r = 0,6\ \Omega$$

**Option 3:**

$$\text{emf} = I(R + r)$$
$$12 = 4(2,4 + r)$$
$$\therefore r = 0,6\ \Omega$$

(3 marks)

**Question 3**

**Option 1:**

$$\text{emf} = IR + Ir$$
$$12 = 6(R + 0,6)$$
$$R_{\text{ext}} = 1,4\ \Omega$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$
$$\frac{1}{1,4} = \frac{1}{2,4} + \frac{1}{R}$$
$$R = 3,36\ \Omega$$

Each tail lamp: $R = 1,68\ \Omega$

**Option 2:**

$$\text{Emf} = V_{\text{terminal}} + Ir$$
$$12 = V_{\text{terminal}} + 6(0,6)$$
$$\therefore V_{\text{terminal}} = 8,4\text{ V}$$

$$I_{2,4\ \Omega} = \frac{V}{R} = \frac{8,4}{2,4} = 3,5\text{ A}$$

$$I_{\text{tail lamps}} = 6 - 3,5 = 2,5\text{ A}$$

$$R_{\text{tail lamps}} = \frac{V}{I} = \frac{8,4}{2,5} = 3,36\ \Omega$$

$$R_{\text{tail lamp}} = 1,68\ \Omega$$

**Option 3:**

$$V = IR$$
$$12 = 6(R)$$
$$R_{ext} = 2\ \Omega$$

$$R_{parallel} = 2 - 0,6$$
$$= 1,4\ \Omega$$
$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$
$$\frac{1}{1,4} = \frac{1}{2,4} + \frac{1}{R}$$
$$R = 3,36\ \Omega$$

Each tail lamp: $R = 1,68\ \Omega$

**Option 4:**

For parallel combination: $I_1 + I_2 = 6$ A

$$\therefore \frac{V}{2,4} + \frac{V}{R_{\text{tail lamps}}} = 6$$
$$8,4\left(\frac{1}{2,4} + \frac{1}{R_{\text{tail lamps}}}\right) = 6$$
$$\therefore R_{\text{tail lamps}} = 3,36\ \Omega$$
$$R_{\text{tail lamp}} = 1,68\ \Omega$$

(5 marks)

**Question 4**

Increases. The resistance increases and the current decreases. So $Ir$ (lost volts) must decrease which leads to an increase in the voltage. (3 marks)

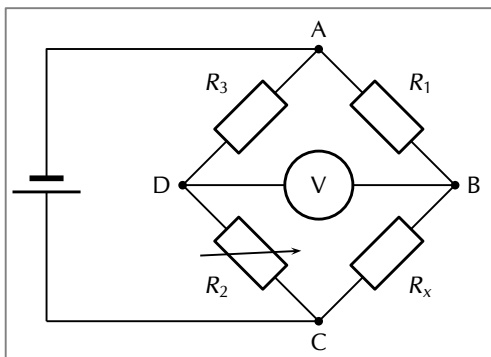
**[TOTAL: 15 marks]**

**FACT**

The Wheatstone bridge was invented by Samuel Hunter Christie in 1833 and improved and popularised by Sir Charles Wheatstone in 1843.

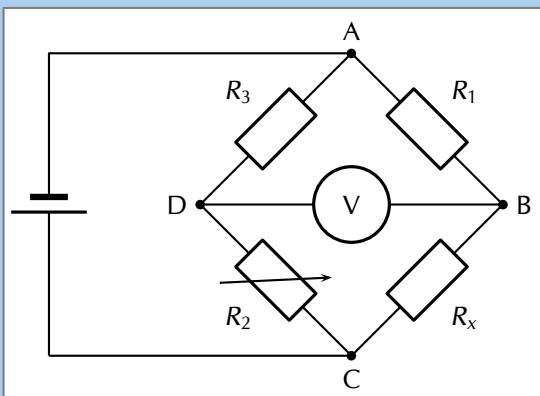
## 10.5 Extension: Wheatstone bridge [Not examinable] ES-CPZ

Using what we know about parallel networks of resistors we can devise another method of finding an unknown resistance, the *Wheatstone bridge*. A Wheatstone bridge is a measuring instrument that is used to measure an unknown electrical resistance by balancing two legs of a bridge circuit, one leg of which includes the unknown component. Its operation is similar to the original potentiometer except that in potentiometer circuits the meter used is a sensitive galvanometer.

Despite the fact that we have given this circuit a special name, it is just a circuit containing a parallel configuration of four resistors. This is not actually a new concept, this particular configuration is just particularly useful.

In the circuit of the Wheatstone bridge, $R_x$ is the unknown resistance. $R_1$, $R_2$ and $R_3$ are resistors of known resistance and the resistance of $R_2$ is adjustable. If the ratio of $R_2$: $R_1$ is equal to the ratio of $R_x$: $R_3$, then the potential difference between the two midpoints will be zero and no current will flow between the midpoints. In order to determine the unknown resistance, $R_2$ is varied until this condition is reached. That is when the voltmeter reads 0 V.

**Worked example 11: Wheatstone bridge**

***QUESTION***

What is the resistance of the unknown resistor $R_x$ in the diagram below if $R_1 = 4\ \Omega$ $R_2 = 8\ \Omega$ and $R_3 = 6\ \Omega$.

***SOLUTION***

**Step 1: Determine how to approach the problem**

The arrangement is a Wheatstone bridge. So we use the equation:

$$R_x : R_3 = R_2 : R_1$$

**Step 2: Solve the problem**

$$R_x : R_3 = R_2 : R_1$$
$$R_x : 6 = 8 : 4$$
$$R_x = 12\ \Omega$$

**Step 3: Write the final answer**

The resistance of the unknown resistor is 12 Ω.

## 10.6 Chapter summary ESCQ2

See presentation: 27XW at www.everythingscience.co.za

1. Ohm's Law governs the relationship between current and potential difference for a circuit element at constant temperature. Mathematically we write $I = \frac{V}{R}$.
2. Conductors that obey Ohm's Law are called ohmic conductors; those that do not are called non-ohmic conductors.
3. Ohm's Law can be applied to a single circuit element or the circuit as a whole (if the components are ohmic).
4. The equivalent resistance of resistors in series ($R_s$) can be calculated as follows: $R_s = R_1 + R_2 + R_3 + ... + R_n$
5. The equivalent resistance of resistors in parallel ($R_p$) can be calculated as follows: $\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + ... + \frac{1}{R_n}$
6. Real batteries have an internal resistance.
7. The potential difference $V$ of the battery is related to its emf $\mathcal{E}$ and internal resistance $r$ by:

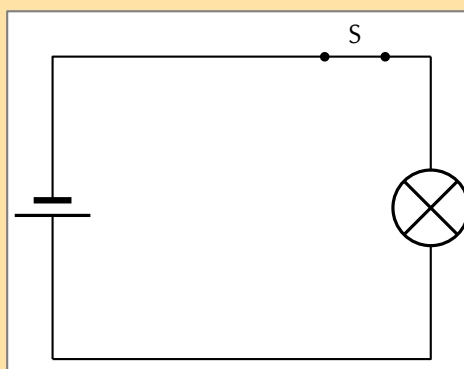
$$\mathcal{E} = V_{\text{load}} + V_{\text{internal resistance}}$$
or
$$\mathcal{E} = IR_{Ext} + Ir$$

8. The external resistance in the circuit is referred to as the load.

| Physical Quantities | | |
|---|---|---|
| **Quantity** | **Unit name** | **Unit symbol** |
| Current ($I$) | Amperes | A |
| Electrical energy ($E$) | Joules | J |
| Power ($P$) | Watts | W |
| Resistance ($R$) | Ohms | Ω |
| Voltage / Potential difference ($V$) | Volts | V |

Table 10.1: Units used in **electric circuits**

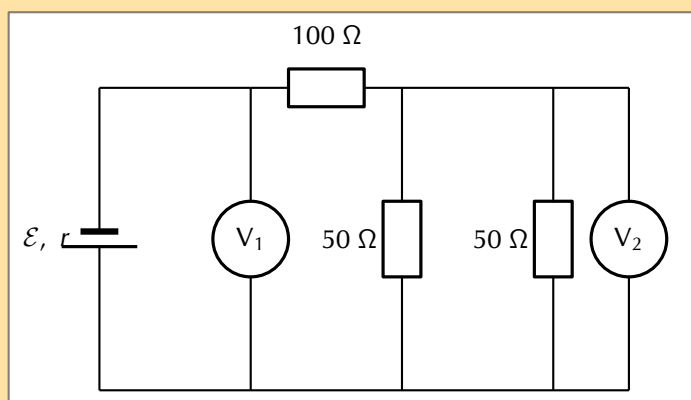
**Exercise 10 – 3:**

1. [IEB 2001/11 HG1] - **Emf**
   a) Explain the meaning of each of these two statements:
      i. "The current through the battery is 50 mA."
      ii. "The emf of the battery is 6 V."
   b) A battery tester measures the current supplied when the battery is connected to a resistor of 100 Ω. If the current is less than 50 mA, the battery is "flat" (it needs to be replaced). Calculate the maximum internal resistance of a 6 V battery that will pass the test.
2. [IEB 2005/11 HG] The electric circuit of a torch consists of a cell, a switch and a small light bulb, as shown in the diagram below.

The electric torch is designed to use a D-type cell, but the only cell that is available for use is an AA-type cell. The specifications of these two types of cells are shown in the table below:

| Cell | emf | Appliance for which it is designed | Current drawn from cell when connected to the appliance for which it is designed |
|---|---|---|---|
| D | 1,5 V | torch | 300 mA |
| AA | 1,5 V | TV remote control | 30 mA |

What is likely to happen and why does it happen when the AA-type cell replaces the D-type cell in the electric torch circuit?

| | What happens | Why it happens |
|---|---|---|
| (a) | the bulb is dimmer | the AA-type cell has greater internal resistance |
| (b) | the bulb is dimmer | the AA-type cell has less internal resistance |
| (c) | the brightness of the bulb is the same | the AA-type cell has the same internal resistance |
| (d) | the bulb is brighter | the AA-type cell has less internal resistance |

3. [IEB 2005/11 HG1] A battery of emf $\varepsilon$ and internal resistance r = 25 Ω is connected to this arrangement of resistors.

The resistances of voltmeters $V_1$ and $V_2$ are so high that they do not affect the current in the circuit.

a) Explain what is meant by "the emf of a battery".
   The power dissipated in the 100 Ω resistor is 0,81 W.
b) Calculate the current in the 100 Ω resistor.
c) Calculate the reading on voltmeter $V_2$.
d) Calculate the reading on voltmeter $V_1$.
e) Calculate the emf of the battery.

4. [SC 2003/11] A kettle is marked 240 V; 1500 W.

a) Calculate the resistance of the kettle when operating according to the above specifications.

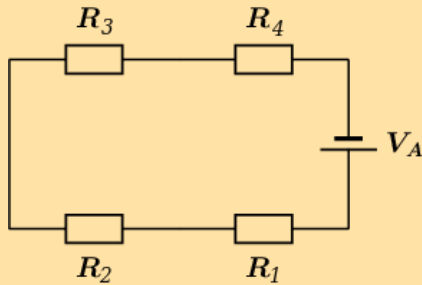
b) If the kettle takes 3 minutes to boil some water, calculate the amount of electrical energy transferred to the kettle.

5. [IEB 2001/11 HG1] - **Electric Eels**

   Electric eels have a series of cells from head to tail. When the cells are activated by a nerve impulse, a potential difference is created from head to tail. A healthy electric eel can produce a potential difference of 600 V.

   a) What is meant by "a potential difference of 600 V"?

   b) How much energy is transferred when an electron is moved through a potential difference of 600 V?

6. The diagram shows an electric circuit consisting of a battery and four resistors.

   The **potential difference** (voltage) over the battery is $V_A = 7{,}6$ V

   The the resistors are rated as follows:

   - $R_1 = 4{,}7\ \Omega$
   - $R_2 = 6{,}9\ \Omega$
   - $R_3 = 4{,}9\ \Omega$
   - $R_4 = 4{,}3\ \Omega$

   Assume that positive charge is flowing in the circuit (conventional current).

   Using the concepts of **Ohm's law**, and **electric circuits**, determine the following:

   a) What type of circuit is shown in the diagram?

   b) What is the **total equivalent resistance** $R_{eq}$ of the circuit?

   - round your answer to 1 digit after the decimal comma
   - use the values for any physical constants you might need, as listed here: http://www.everythingscience.co.za/physical-constants

   c) **Question 3**

   What is the potential difference (voltage) across $R_1$, or $V_1$ ?

   - round your answer to 3 digits after the decimal comma
   - use the values for any physical constants you might need, as listed here: http://www.everythingscience.co.za/physical-constants

   d) What is the potential difference (voltage) across $R_2$, $R_3$, and $R_4$, or $V_2$, $V_3$, and $V_4$?

   - round your answers to 3 digits after the decimal comma
   - use the values for any physical constants you might need, as listed here: http://www.everythingscience.co.za/physical-constants

7. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27XX 2. 27XY 3. 27XZ 4. 27Y2 5. 27Y3 6. 27Y4

# CHAPTER

## *Electrodynamics*

## 11.1 Introduction ESCQ3

In Grade 11 you learnt how a magnetic field is generated around a current-carrying conductor. You also learnt how a current is generated in a conductor that moves in a magnetic field or in a stationay conductor in a changing magnetic field. This chapter describes how conductors moving in a magnetic field are applied in the real-world.

Today, currents induced by magnetic fields are essential to our technological society. The ubiquitous generator—found in automobiles, on bicycles, in nuclear power plants, and so on—uses magnetism to generate current. Other devices that use magnetism to induce currents include pickup coils in electric guitars, transformers of every size, certain microphones, airport security gates, and damping mechanisms on sensitive chemical balances. Not so familiar perhaps, but important nevertheless, is that the behavior of AC circuits depends strongly on the effect of magnetic fields on currents.

See video: 27Y5 at www.everythingscience.co.za

## 11.2 Electrical machines - generators and motors ESCQ4

We have seen that when a conductor is moved in a magnetic field or when a magnet is moved near a conductor, a current flows in the conductor. The amount of current depends on:

- the speed at which the conductor experiences a changing magnetic field,
- the number of coils that make up the conductor, and
- the position of the plane of the conductor with respect to the magnetic field.

The effect of the orientation of the conductor with respect to the magnetic field is illustrated in Figure 11.1.

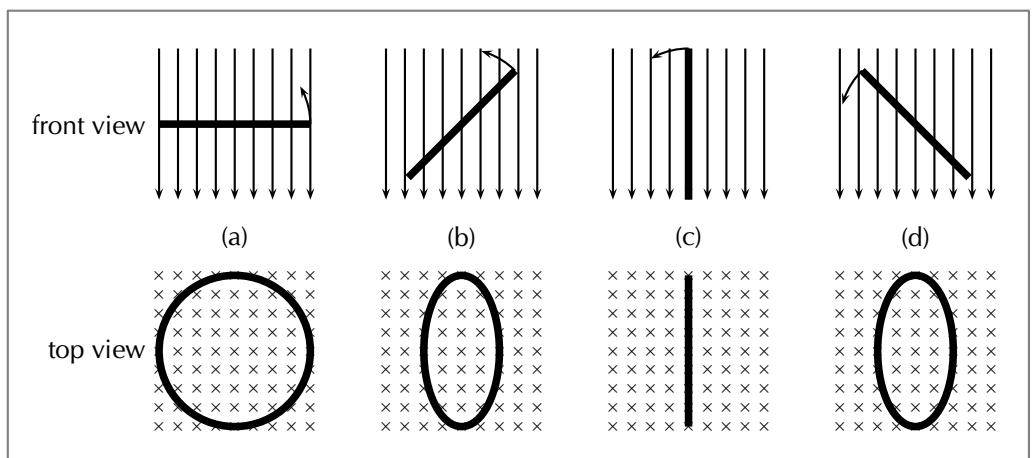



Figure 11.1: Series of figures showing that the magnetic flux through a conductor is dependent on the angle that the plane of the conductor makes with the magnetic field. The greatest flux passes through the conductor when the plane of the conductor is perpendicular to the magnetic field lines as in Figure 11.1 (a). The number of field lines passing through the conductor decreases, as the conductor rotates until it is parallel to the magnetic field Figure 11.1 (c).

If the emf induced and the current in the conductor were plotted as a function of the angle between the plane of the conductor and the magnetic field for a conductor that has a constant speed of rotation, then the induced emf and current would vary as shown in 11.2. The current alternates around zero and is known as an *alternating current* (abbreviated AC).

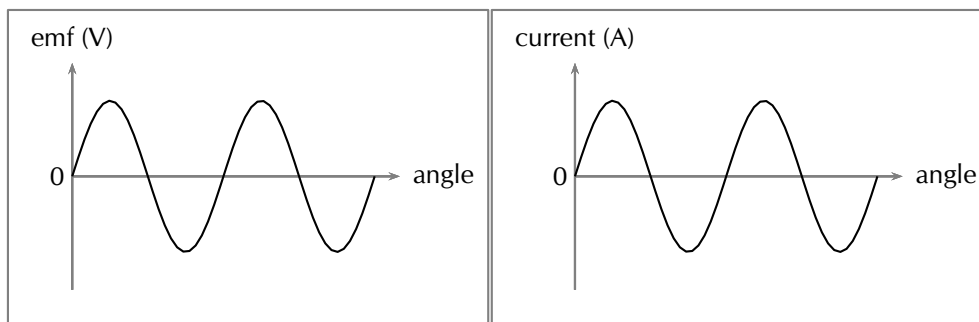



Figure 11.2: Variation of induced emf and current as the angle between the plane of a conductor and the magnetic field changes.

The angle changes as a function of time so the above plots can be mapped onto the time axis as well.

Recall Faraday's Law, which you learnt about in Grade 11:

**DEFINITION:** *Faraday's Law*

The emf, $\mathcal{E}$, induced around a single loop of conductor is proportional to the rate of change of the magnetic flux, $\phi$, through the area, $A$, of the loop. This can be stated mathematically as:

$$\mathcal{E} = -N\frac{\Delta\phi}{\Delta t}$$

where $\phi = B \cdot A\cos\theta$ and $B$ is the strength of the magnetic field.

Faraday's Law relates induced emf to the rate of change of magnetic flux, which is the product of the magnetic field strength and the cross-sectional area the field lines pass through. The cross-sectional area changes as the loop of the conductor rotates which gives rise the $\cos\theta$ factor. $\theta$ is the angle between the normal to the surface area of the loop of the conductor and the magnetic field. As the closed loop conductor changes orientation with respect to the magnetic field, the amount of magnetic flux through the area of the loop changes and an emf is induced in the conducting loop.

## Electrical generators ESCQ5

## AC generator ESCQ6

The principle of rotating a conductor in a magnetic field to generate current is used in electrical generators. A generator converts mechanical energy (motion) into electrical energy.

**DEFINITION:** *Generator*

A generator is a device that converts mechanical energy into electrical energy.

**FACT**
AC generators are also known as alternators. They are found in motor cars to charge the car battery.

The layout of a simple AC generator is shown in Figure 11.3. The conductor is formed of a coil of wire, placed inside a magnetic field. The conductor is manually rotated within the magnetic field. This generates an alternating emf. The alternating current needs to be transmitted from the conductor to the load, which is the system requiring the electrical energy to function.

The load and the conductor are connected by a slip ring. A slip ring is a connector which is able to transmit electricity between rotating portions of a machine. It is made up of a ring and brushes, one of which is stationary with respect to the other. Here, the ring attaches to the conductor and the brushes are attached to the load. Current is generated in the rotating conductor, passes into the slip rings, which rotate against the brushes. The current is transmitted through the brushes into the load, and the system is thus powered.

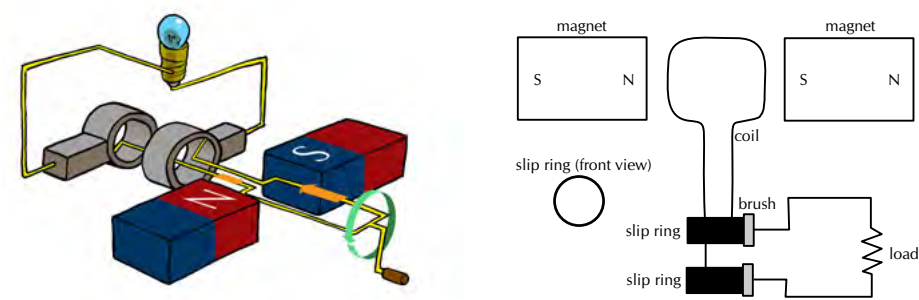



Figure 11.3: Layout of an alternating current generator.

The direction of the current changes with every half turn of the coil. As one side of the loop moves to the other pole of the magnetic field, the current in the loop changes direction. This type of current which changes direction is known as alternating current and Figure 11.4 shows how it comes about as the conductor rotates.

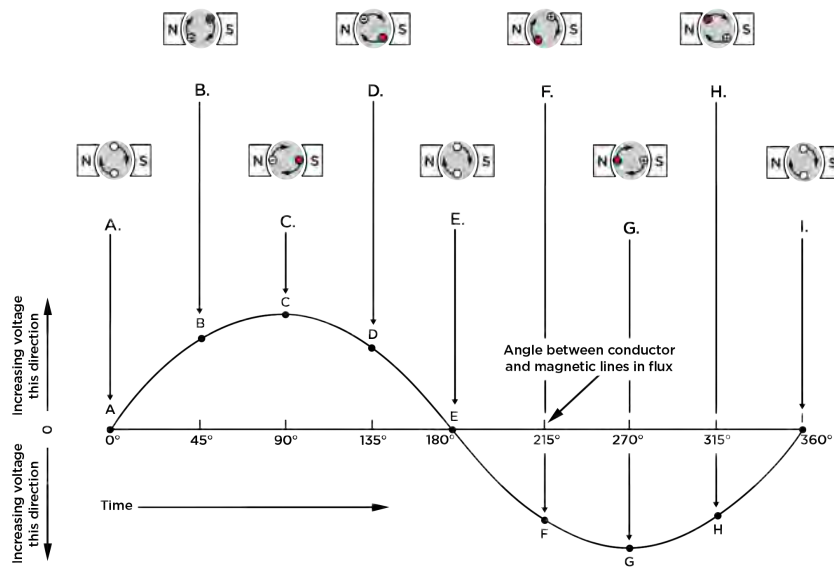



Figure 11.4: The red (solid) dots represent current coming out of the page and the crosses show current going into the page.

## DC generator ESCQ7

A simple DC generator is constructed the same way as an AC generator except that there is one slip ring which is split into two pieces, called a commutator, so the current in the external circuit does not change direction. The layout of a DC generator is shown in Figure 11.5. The split-ring commutator accommodates for the change in direction of the current in the loop, thus creating direct current (DC) current going through the brushes and out to the circuit. The current in the loop does reverse direction but if you look carefully at the 2D image you will see that the section of the split-ring commutator also changes which side of the circuit it is touching. If the current changes direction at the same time that the commutator swaps sides the external circuit will always have current going in the same direction.

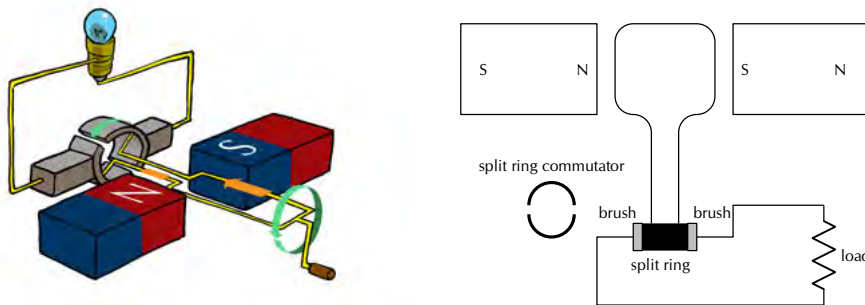



Figure 11.5: Layout of a direct current generator.

The shape of the emf from a DC generator is shown in Figure 11.6. The emf is not steady but is the absolute value of a sine/cosine wave.

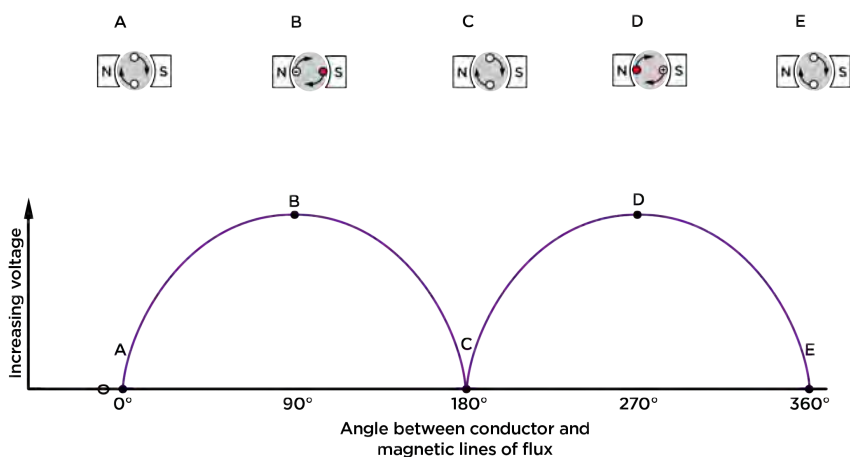



Figure 11.6: Variation of emf in a DC generator.

## AC versus DC generators ESCQ8

The problems involved with making and breaking electrical contact with a moving coil are sparking and heat, especially if the generator is turning at high speed. If the atmosphere surrounding the machine contains flammable or explosive vapours, the practical problems of spark-producing brush contacts are even greater.

If the magnetic field, rather than the coil/conductor is rotated, then brushes are not needed in an AC generator (alternator), so an alternator will not have the same problems as DC generators. The same benefits of AC over DC for generator design also apply to electric motors. While DC motors need brushes to make electrical contact with moving coils of wire, AC motors do not. In fact, AC and DC motor designs are very similar to their generator counterparts. The AC motor is depends on the reversing magnetic field produced by alternating current through its stationary coils of wire to make the magnet rotate. The DC motor depends on the brush contacts making and breaking connections to reverse current through the rotating coil every 1/2 rotation (180 degrees).

## Electric motors ESCQ9

The basic principles of operation for an electric motor are the same as that of a generator, except that a motor converts electrical energy into mechanical energy (motion).

**DEFINITION:** *Electric motor*

An electric motor is a device that converts electrical energy into mechanical energy.

If one were to place a moving charged particle in a magnetic field, it would experience a force called the **Lorentz force**.

**DEFINITION:** *The Lorentz Force*

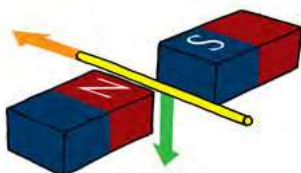
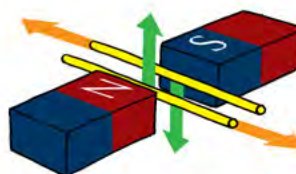
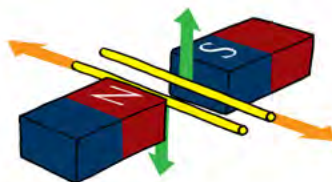
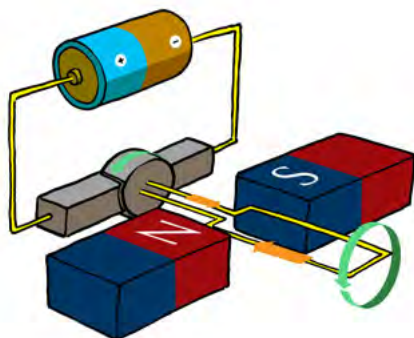
The Lorentz force is the force experienced by a moving charged particle in an electric and magnetic field. The magnetic component is:

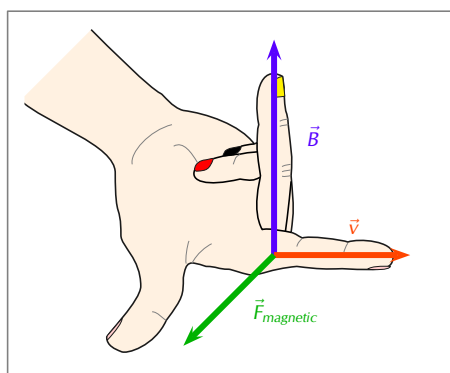
$$F = qvB$$

where $F$ is the force (in newtons, N), $q$ is the electric charge (in coulombs, C), $v$ is the velocity of the charged particle (in $m \cdot s^{-1}$) and $B$ is the magnetic field strength (in teslas, T).

In this diagram a positive charge is shown moving between two opposite poles of magnets. The direction of the charge's motion is indicated by the orange arrow. It will experience a Lorentz force which will be in the direction of the green arrow.

A current-carrying conductor, where the current is in the direction of the orange arrow, will also experience a magnetic force, the green arrow, due to the Lorentz force on the individual charges moving in the current flow.

**FACT**
The force on a current-carrying conductor due to a magnetic field is called Ampere's law.

If the direction of the current is reversed, for the same magentic field direction, then the direction of the magnetic force will also be reversed as indiced in this diagram.

We can see that if there are two parallel conductors with current in opposite direcions they will experience magnetic forces in opposite directions.

An electric motor works by using a source of emf to make a current flow in a loop of conductor such that the Lorentz force on opposite sides of the loop are in opposite directions which can cause the loop to rotate about a central axis.

The direction of the magnetic force is perpendicular to both the direction of the flow of current and the direction of the magnetic field and can be found using the **Right Hand Rule** as shown in the picture below. Use your *right hand*; your first finger points in the direction of the current, your second finger in the direction of the magnetic field and your thumb will then point in the direction of the force.

Both motors and generators can be explained in terms of a coil that rotates in a magnetic field. In a generator the coil is attached to an external circuit that is turned, resulting in a changing flux that induces an emf. In a motor, a current-carrying coil in a magnetic field experiences a force on both sides of the coil, creating a twisting force (called a *torque*, pronounce like 'talk') which makes it turn.

If the current is AC, the two slip rings are required to create an AC motor. An AC motor is shown in 11.7

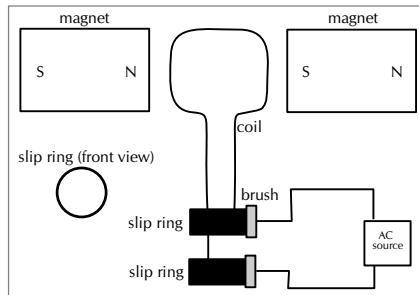



Figure 11.7: Layout of an AC motor.

If the current is DC, split-ring commutators are required to create a DC motor. This is shown in 11.8.

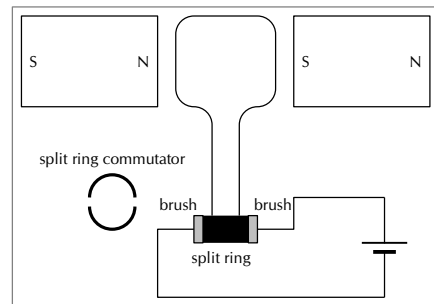



Figure 11.8: Layout of a direct current motor.

## Real-life applications ESCQB

### Cars

A car contains an alternator. When the car's engine is running the alternator charges its battery and powers the car's electric system.

**Project: Alternators**

Try to find out the different current values produced by alternators for different types of machines. Compare these to understand what numbers make sense in the real world. You will find different values for cars, trucks, buses, boats etc. Try to find out what other machines might have alternators.

A car also contains a DC electric motor, the starter motor, to turn over the engine to start it. A starter motor consists of the very powerful DC electric motor and starter solenoid that is attached to the motor. A starter motor requires a very high current to crank the engine and is connected to the battery with large cables to carry large current.

### Electricity generation

In order to produce electricity for mass distribution (to homes, offices, factories and so forth), AC generators are usually used. The electricity produced by massive power plants usually has a low voltage which is converted to high voltage. It is more efficient to distribute electricity over long distances in the form of high voltage power lines.

The high voltages are then coverted to 240 V for consumption in homes and offices. This is usually done within a few kilometres of where it will be used.

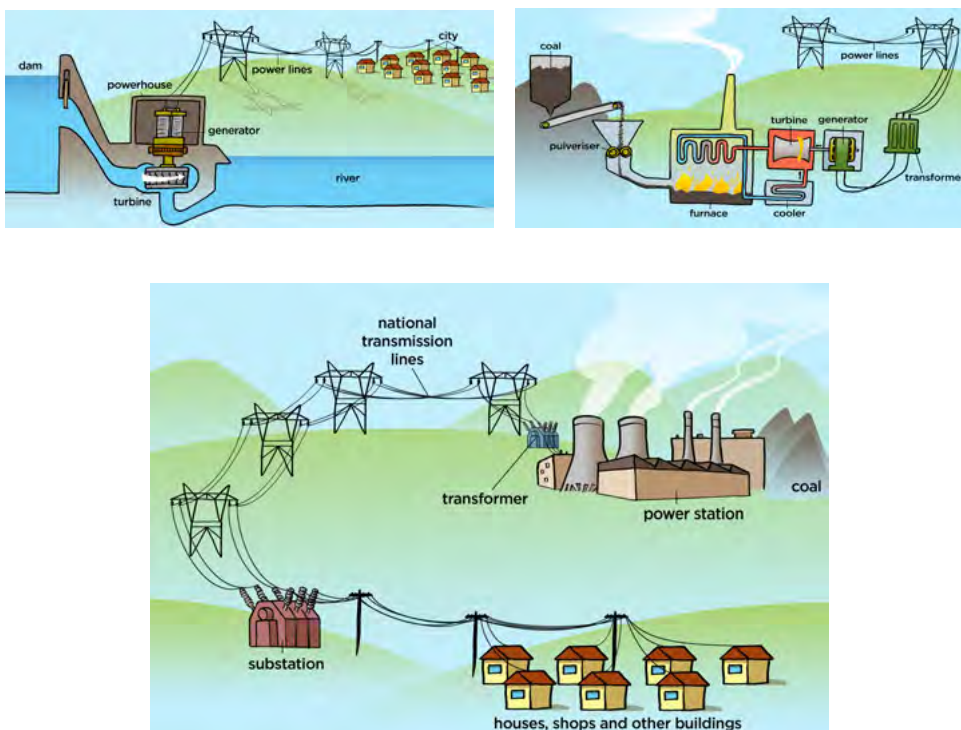



Figure 11.9: AC generators are used at power plants (all types, hydro- and coal-plants shown in top row) to generate electricity.

### Exercise 11 – 1: Generators and motors

1. State the difference between a generator and a motor.
2. Use Faraday's Law to explain why a current is induced in a coil that is rotated in a magnetic field.
3. Explain the basic principle of an AC generator in which a coil is mechanically rotated in a magnetic field. Draw a diagram to support your answer.
4. Explain how a DC generator works. Draw a diagram to support your answer. Also, describe how a DC generator differs from an AC generator.
5. Explain why a current-carrying coil placed in a magnetic field (but not parallel to the field) will turn. Refer to the force exerted on moving charges by a magnetic field and the torque on the coil.
6. Explain the basic principle of an electric motor. Draw a diagram to support your answer.
7. Give examples of the use of AC and DC generators.
8. Give examples of the uses of motors.
9. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27Y6 2. 27Y7 3. 27Y8 4. 27Y9 5. 27YB 6. 27YC
7. 27YD 8. 27YF

**FACT**
In South Africa alternating current is generated at a frequency of 50 Hz.

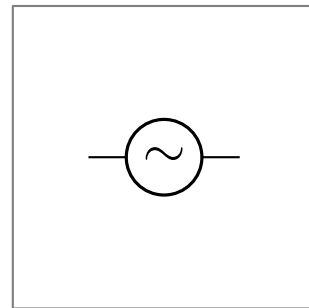
## 11.3 Alternating current ESCQC

Most students learning about electricity begin with what is known as *direct current* (DC), which is electricity flowing in one direction only. DC is the kind of electricity made by a battery, with definite positive and negative terminals.

However, we have seen that the electricity produced by some generators constantly alternates (switches direction) and is therefore known as *alternating current* (AC). There are a number of advantages to AC current, the main advantage to AC is that the voltage can be changed using transformers. That means that the voltage can be "stepped up" at power stations to a very high voltage so that electrical energy can be transmitted along power lines at low current and therefore experience low energy loss due to heating. The voltage can then be stepped down for use in buildings and street lights.

A list of the advantages of AC current:

- Easy to be transformed (step up or step down using a transformer).
- Easier to convert from AC to DC than from DC to AC.
- Easier to generate.
- It can be transmitted at high voltage and low current over long distances with less energy lost.
- High frequency used in AC makes it suitable for motors.

The circuit symbol for alternating current is:

### Current and voltage ESCQD

In an ideal DC circuit, current and voltage are constant. In an AC circuit, current and voltage vary with time. The value of the current or voltage at any specific time is called the *instantaneous current or voltage* and is calculated as follows:

$$i = I_{\text{max}} \sin(\omega t)$$
$$v = V_{\text{max}} \sin(\omega t)$$

$i$ is the instantaneous current. $I_{\text{max}}$ is the maximum current. $v$ is the instantaneous voltage. $V_{\text{max}}$ is the maximum voltage. $f$ is the frequency of the AC and t is the time at which the instantaneous current or voltage is being calculated.

The value we use for AC is known as the root mean square (rms) average. This is the same as what the DC voltage would be for the same source and is defined as:

$$I_{rms} = \frac{I_{\text{max}}}{\sqrt{2}}$$
$$V_{rms} = \frac{V_{\text{max}}}{\sqrt{2}}$$

Since AC varies sinusoidally, with as much positive as negative, doing a straight average would get you zero for the average voltage. The rms value by-passes this problem.

**Worked example 1: Laptop transformer**

***QUESTION***

The transformer for the laptop on which this book was written has the following information:

- INPUT: 100-240 V; 1,5 A; 50/60 Hz
- OUTPUT:20 V; 3,25 A

What changes from input to output, apart from the voltage and current values, and what does that imply? In addition, calculate the rms (root mean square) current and voltage values for the input and/or output as appropriate.

***SOLUTION***

**Step 1: Comparing input and output**

The input description includes a frequency because it is designed for regular household use where we use alternating current. The output doesn't include a frequency. This implies that the output is not alternating current. This means that the output voltage and current will be constant with time.

**Step 2: RMS values**

Root mean square values are only applicable when dealing with alternating current. The transformer takes alternating current input and produces direct current output, this means that we only need to determine the rms values for the input.

$$V_{\text{rms}} = \frac{V_{\text{max}}}{\sqrt{2}}$$
$$V_{\text{rms}} = \frac{240\text{ V}}{\sqrt{2}}$$
$$= 169{,}71\text{ V}$$

$$I_{\text{rms}} = \frac{I_{\text{max}}}{\sqrt{2}}$$
$$I_{\text{rms}} = \frac{1{,}5\text{ A}}{\sqrt{2}}$$
$$= 1{,}06\text{ A}$$

Therefore $V_{\text{rms}} = 169{,}71$ V

Therefore $I_{\text{rms}} = 1{,}06$ A

**Worked example 2: Camera battery charger**

***QUESTION***

A camera charger has the following information:

- INPUT: 100-240 V; 0,085 A (100 V) - 0,05 A (240 V) ; 50/60 Hz
- OUTPUT:4,2 V; 0,7 A

Calculate the rms (root mean square) current and voltage values for both 100 V and 240 V input.

***SOLUTION***

**Step 1: Understanding the two cases**

The reason the transformer has the different input voltages listed is because it may be used internationally and not all countries use the same household voltage. The transformers purpose is to ensure that the output is consistent regardless of the input

voltage. The different input voltages of 100 V and 240 V result in different input current values. This is why two different current values are listed under input but the voltage in parentheses tells you which case they are applicable to.

The cases are:

- **100 V:** 0,085 A
- **240 V:** 0,05 A

**Step 2: Input voltage of 100 V**

$$V_{\text{rms}} = \frac{V_{\text{max}}}{\sqrt{2}}$$
$$V_{\text{rms}} = \frac{100\text{ V}}{\sqrt{2}} = 70{,}71\text{ V}$$

Therefore $V_{\text{rms}} = 70{,}71$ V

$$I_{\text{rms}} = \frac{I_{\text{max}}}{\sqrt{2}}$$
$$I_{\text{rms}} = \frac{0{,}085\text{ A}}{\sqrt{2}} = 0{,}06\text{ A}$$

Therefore $I_{\text{rms}} = 0{,}06$ A

**Step 3: Input voltage of 240 V**

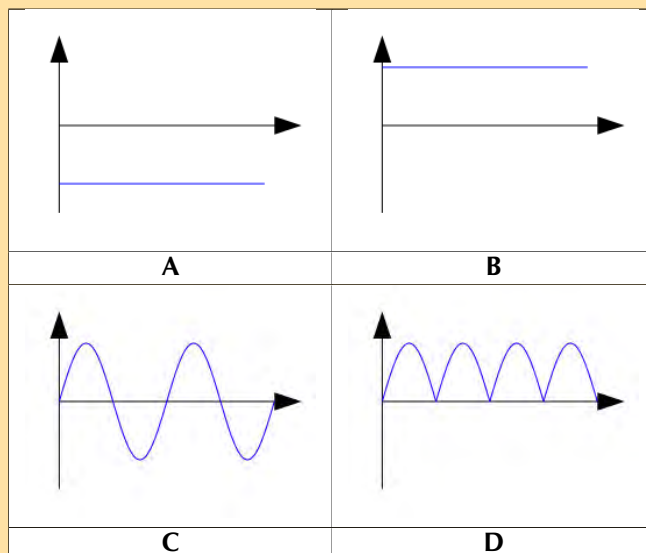
$$V_{\text{rms}} = \frac{V_{\text{max}}}{\sqrt{2}}$$
$$V_{\text{rms}} = \frac{240\text{ V}}{\sqrt{2}} = 169{,}71\text{ V}$$

Therefore $V_{\text{rms}} = 169{,}71$ V

$$I_{\text{rms}} = \frac{I_{\text{max}}}{\sqrt{2}}$$
$$I_{\text{rms}} = \frac{0{,}5\text{ A}}{\sqrt{2}} = 0{,}35\text{ A}$$

Therefore $I_{\text{rms}} = 0{,}35$ A

**Exercise 11 – 2: Alternating current**

1. Explain the advantages of alternating current.
2. Which of the following graphs correctly shows the current vs. time graph for an AC generator?

3. Write expressions for the current and voltage in an AC circuit.
4. Define the rms (root mean square) values for current and voltage for AC.
5. What is the frequency of the AC generated in South Africa?
6. If $V_{max}$ at a power station generator is 340 V AC, what is the mains supply (rms voltage) in our household?
7. Given: $I_{max}$ is 10 A
   Calculate the rms (root mean square) current to two decimal places.
8. Given: $V_{max}$ is 266 V
   Calculate the rms (root mean square) voltage to two decimal places.
9. Draw a graph of voltage vs time and current vs time for an AC circuit.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27YG 2. 27YH 3. 27YJ 4. 27YK 5. 27YM 6. 27YN
7. 27YP 8. 27YQ 9. 27YR

## Power ESCQF

If the current and voltage are functions of time, so they are always changing, then so will the power that is dissipated in any circuit element. In circuits which contain only ohmic resistors the **average** power dissipated in any component can be calculated in terms of the rms values.

$$\begin{aligned} P_{av} &= I_{rms}V_{rms} \\ &= \frac{I_{max}}{\sqrt{2}}\frac{V_{max}}{\sqrt{2}} \\ &= \frac{1}{2}I_{max}V_{max} \end{aligned}$$

You might ask why we don't need to use an rms value for power. In an AC circuit both the current and voltage have the same sign so they are both either positive or negative. This means that power, the product of the two is always positive. If power is always positive then the average value won't be zero as in the case of current or voltage in AC circuits.

### Worked example 3: Laptop transformer power

***QUESTION***

The transformer for a laptop has the following information:

- INPUT: 100-240 V; 1,5 A; 50/60 Hz
- OUTPUT:20 V; 3,25 A

Using the input values and assuming 240 V, what is the average power dissipated in the transformer?

### SOLUTION

**Step 1: RMS values**

As calculated previously:

$$V_{\text{rms}} = \frac{V_{\text{max}}}{\sqrt{2}}$$
$$V_{\text{rms}} = \frac{240\text{ V}}{\sqrt{2}}$$
$$= 169{,}71\text{ V}$$

$$I_{\text{rms}} = \frac{I_{\text{max}}}{\sqrt{2}}$$
$$I_{\text{rms}} = \frac{1{,}5\text{ A}}{\sqrt{2}}$$
$$= 1{,}06\text{ A}$$

Therefore $V_{\text{rms}} = 169{,}71\text{ V}$

Therefore $I_{\text{rms}} = 1{,}06\text{ A}$

**Step 2: Average power**

$$P_{av} = I_{rms}V_{rms}$$
$$= 1{,}06\text{ A} \cdot 169{,}71\text{ V}$$
$$= 179{,}89\text{ W}$$

**Worked example 4: Motors and generators [NSC 2011 Paper 1]**

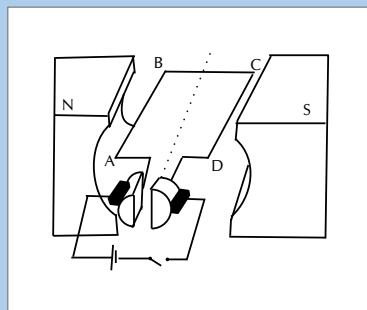
### QUESTION

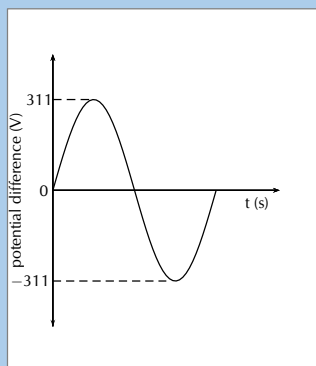
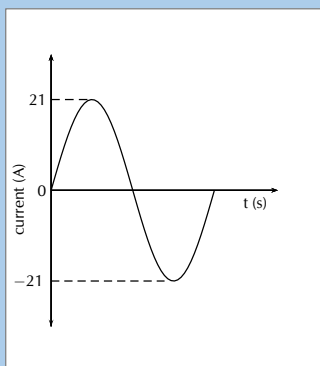
Diesel-electric trains make use of electric motors as well as generators.

1. The table below compares a motor and a generator in terms of the type of energy conversion and the underlying principle on which each operates. Complete the table by writing down only the question number (11.1.1–11.1.4) in the ANSWER BOOK and next to each number the answer.

| | TYPE OF ENERGY CONVERSION | PRINCIPLE OF OPERATION |
|---|---|---|
| **Motor** | 11.1.1 | 11.1.3 |
| **Generator** | 11.1.2 | 11.1.4 |

(4 marks)

2. The simplified diagram below represents an electric motor.

Give a reason why the section of the coil labelled **BC** in the above diagram does not experience a magnetic force whilst the coil is in the position as shown. (2 marks)

3. Graphs of the current and potential difference outputs of an AC generator are shown below.

Calculate the average power output of this generator. (6 marks)

**[TOTAL: 12 marks]**

***SOLUTION***

**Question 1**

1. Electrical (energy) to mechanical (kinetic) energy
2. Mechanical (kinetic) energy to electrical (energy)
3. Motor effect
4. Electromagnetic induction

(4 marks)

**Question 2**

BC (conductor) is parallel to the magnetic field.

**OR**

Open switch, no current (2 marks)

**Question 3**

**Option 1:**

$$\begin{aligned} P_{ave} &= V_{rms} I_{rms} \\ &= \frac{V_{max}}{\sqrt{2}} \cdot \frac{I_{max}}{\sqrt{2}} \\ &= \frac{(311)(21)}{2} \\ &= 3265{,}5 \text{ W} \end{aligned}$$

**OR**

$$\begin{aligned} P_{max} &= V_{max} I_{max} \\ &= (311)(21) \\ &= 6531 \text{ W} \end{aligned}$$

$$\begin{aligned} \therefore P_{ave} &= \frac{P_{max}}{2} \\ &= \frac{6531}{2} \\ &= 3265{,}5 \text{ W} \end{aligned}$$

**Option 2:**

$$\begin{aligned} V_{rms} &= \frac{V_{max}}{\sqrt{2}} \\ &= \frac{311}{\sqrt{2}} \\ &= 219{,}91 \text{ V} \end{aligned}$$

$$\begin{aligned} I_{rms} &= \frac{I_{max}}{\sqrt{2}} \\ &= \frac{21}{\sqrt{2}} \\ &= 14{,}85 \text{ A} \end{aligned}$$

$$\begin{aligned} P_{ave} &= V_{rms} I_{rms} \\ &= (219{,}91)(14{,}85) \\ &= 3265{,}66 \text{ W} \end{aligned}$$

**Option 3:**

$$R = \frac{V}{I} = \frac{311}{21} = 14,81\ \Omega$$

$$I_{\text{rms}} = \frac{I_{\text{max}}}{\sqrt{2}} = \frac{21}{\sqrt{2}} = 14,85\ \text{A}$$

$$P_{\text{ave}} = I_{\text{rms}}^2 R = (14,85)^2(14,81) = 3265,83\ \text{W}$$

**Option 4:**

$$R = \frac{V}{I} = \frac{311}{21} = 14,81\ \Omega$$

$$V_{\text{rms}} = \frac{V_{\text{max}}}{\sqrt{2}} = \frac{311}{\sqrt{2}} = 219,91\ \text{V}$$

$$P_{\text{ave}} = \frac{V_{\text{rms}}^2}{R} = \frac{(219,41)^2}{(14,81)} = 3265,83\ \text{W}$$

(6 marks)

**[TOTAL: 12 marks]**

## 11.4 Chapter summary ESCQG

See presentation: 27YS at www.everythingscience.co.za

- Electrical generators convert mechanical energy into electrical energy.
- Electric motors convert electrical energy into mechanical energy.
- There are two types of generators - AC and DC. An AC generator is also called an alternator.
- There are two types of motors - AC and DC.
- Alternating current (AC) has many advantages over direct current (DC) listed previously.
- The root mean square (rms) value of a quantity is the maximum value the quantity can have divided by $\sqrt{2}$.
- RMS values are used for voltage and current when dealing with alternating current, $I_{\text{rms}} = \frac{I_{\text{max}}}{\sqrt{2}}$ and $V_{\text{rms}} = \frac{V_{\text{max}}}{\sqrt{2}}$.
- The average power dissipated in a purely resistive circuit with alternating current is $P_{av} = I_{rms}V_{rms}$.

**Exercise 11 – 3:**

1. [SC 2003/11] Explain the difference between alternating current (AC) and direct current (DC).
2. Explain how an AC generator works. You may use sketches to support your answer.
3. What are the advantages of using an AC motor rather than a DC motor.
4. Explain how a DC motor works.
5. At what frequency is AC generated by Eskom in South Africa?
6. (IEB 2001/11 HG1) - **Work, Energy and Power in Electric Circuits**

   Mr. Smith read through the agreement with Eskom (the electricity provider). He found out that alternating current is supplied to his house at a frequency of 50 Hz. He then consulted a book on electric current, and discovered that alternating current moves to and fro in the conductor. So he refused to pay his Eskom bill on the grounds that every electron that entered his house would leave his house again, so therefore Eskom had supplied him with nothing!

   Was Mr. Smith correct? Or has he misunderstood something about what he is paying for? Explain your answer briefly.
7. You are building a laser that takes alternating current and it requires a very high peak voltage of 180 kV. By your calculations the entire laser setup can be treated at a single resistor with an equivalent resistance of 795 ohms. What is the rms value for the voltage and the current and what is the average power that your laser is dissipating?

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27YT 2. 27YV 3. 27YW 4. 27YX 5. 27YY 6. 27YZ
7. 27Z2

CHAPTER

# *Optical phenomena and properties of matter*

## 12.1 Introduction ESCQH

Many people are using solar power as a source of energy for their homes. Solar power can be used to heat water or to supply electricity. Have you ever noticed solar panels on homes and buildings? Have you ever wondered how solar energy is converted to electrical energy? In this chapter, we examine the process that is used to achieve this energy conversion.
See video: 27Z3 at www.everythingscience.co.za

Figure 12.1: The use of solar cells to supply electricity.

**Key linked concepts**

- Units and unit conversions — Physical Sciences, Grade 10, Science skills
- Equations — Mathematics, Grade 10, Equations and inequalities
- Electronic configuration — Physical Sciences, Grade 10, The atom
- Electromagnetic radiation — Physical Sciences, Grade 10, Electromagnetic radiation

## 12.2 The photoelectric effect ESCQJ

Around the turn of the twentieth century, it was observed by a number of physicists (including Hertz, Thomson and Von Lenard) that when light was shone onto a metal plate, electrons were emitted by the metal. This is called the photoelectric effect. (*photo* for light, *electric* for the electron.)

The characteristics of the photoelectric effect were a surprise and a very important development in modern Physics. To understand why it was a surprise we need to look at the history to understand what physicists were expecting to happen and then understand the implications for Physics going forward.

### History and expectations as to the photoelectric effect ESCQK

In 1887, Heinrich Hertz (a German physicist) noticed that ultraviolet light incident on a metal plate could cause sparks. Metals were known to be good conductors of electricity, because the electrons are more able to move. They should be able to be dislodged if energy were added through the incident light. The problem was that different metals requred different minimum frequencies of light.

The expectation at the time was that electrons would be emitted for any frequency of light, after a delay (for low intensities) during which the electrons absorbed sufficient energy to escape from the metal surface. The higher the intensity the shorter the delay was be as they would absorb energy faster. This was based on the idea that light was a wave continuously delivering energy to the electrons.

It is important to remember that higher frequency light corresponds to higher energy.

The next piece of the puzzle came from Philipp Lenard (a Hungarian physicist) in 1902 when he discovered that the maximum velocity with which electrons are ejected by ultraviolet light is entirely independent of the intensity of light.

His expectation was that at high intensities the electrons would absorb more energy and so would have a greater velocity.

A **paradox** existed as the expectations and the observations did not match.

Albert Einstein (a German physicist) solved this paradox by proposing that light is made up of packets of energy called *quanta* (now called photons) which interacted with the electrons in the metal like particles instead of waves. Each incident photon would transfer all its energy to one electron in the metal.

**DEFINITION:** *The photoelectric effect*

The photoelectric effect is the process whereby an electron is emitted by a substance when light shines on it.

Einstein received the 1921 Nobel Prize for his contribution to understanding the photoelectric effect. His explanation wasn't very popular and took a while to be accepted, in fact, some scientists at the time felt that is was a big mistake.

In the motivation letter for Einstein to be accepted into the Prussian Academy of Science it was specifically mentioned as a mistake:

> *In sum, one can say that there is hardly one among the great problems in which modern physics is so rich to which Einstein has not made a remarkable contribution. That he may sometimes have missed the targeting his speculations, as, for example, in his hypothesis of light-quanta, cannot really be held too much against him, for it is not possible to introduce really new ideas even in the most exact sciences without sometimes taking a risk – A. Pais, "Subtle is the Lord: The Science and the Life of Albert Einstein," New York: Oxford University Press, 1982, p. 382*

## Implications of Einstein's model ESCQM

Einstein's model is consistent with the observation that the electrons were emitted immediately when light was shone on the metal and that the *intensity* of the light made *no difference* to the maximum kinetic energy of the emitted electrons.

The energy needed to knock an electron out of the substance is called the **work function** (symbol $W_0$) of the substance. This is a characteristic of the substance. If the energy of the photon is less than the work function then no electron can be emitted, no matter how many photons strike the substance. We know that the frequency of light is related to the energy, that is why there is a minimum frequency of light that can eject electrons. This minimum frequency we call the cut-off frequency, $f_0$. For a specific colour of light (i.e. a certain frequency or wavelength), the energy of the photons is given by $E = hf = hc/\lambda$, where $h$ is Planck's constant. This tells us that

the $W_0 = hf_0$ .

**DEFINITION:** *Work function*

The minimum energy needed to knock an electron out of a metal is called the **work function** (symbol $W_0$) of the metal. As it is energy, it measured in joules (J).

Energy is conserved so if the photon has a higher energy than $W_0$ then the excess energy goes into the kinetic energy $E_k$ of the electron that was emitted from the substance.

The excess over and above the binding energy is actually the **maximum** kinetic energy the emitted electron can have. This is because not all electrons are on the surface of the substance. For electrons below the surface there is additional energy required to eject the electron from the material which then cannot contribute to the kinetic energy of the electron.

$$E = W_0 + E_{k\ \max}$$
$$E_{k\ \max} = hf - W_0$$

This equation is known as the photo-electric equation.

The last piece of the puzzle is now clear, the question was 'why does increasing the intensity of the light not affect the maximum kinetic energy of the emitted photons?'. The answer is that each emitted electron has absorbed **one** photon, increasing the intensity just increases the number of photons (we expect more electrons but we don't expect their maximum kinetic energy to change).

The discovery and understanding of the photoelectric effect was one of the major breakthroughs in science in the twentieth century as it provided concrete evidence of the particle nature of light. It overturned previously held views that light was composed purely of a continuous transverse wave. On the one hand, the wave nature is a good description of phenomena such as diffraction and interference for light, and on the other hand, the photoelectric effect demonstrates the particle nature of light. This is now known as the 'dual-nature' of light. (dual means two)

Einstein won the 1921 Nobel Prize for Physics for this quantum theory and his explanation of the photoelectric effect.

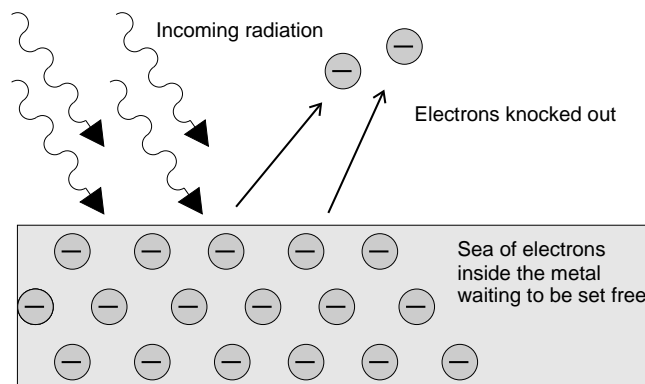



Figure 12.2: The photoelectric effect: Incoming photons on the left hit the electrons inside the metal surface. The electrons absorb the energy from the photons, and are ejected from the metal surface.

We can observe this effect in the following practical demonstration of photoelectric emission. A zinc plate is charged negatively and placed onto the cap of an electroscope. In Figure 12.3, red light is shone onto the zinc plate. There is no change observed even if the intensity (brightness) of the red light is increased. In Figure 12.4, ultraviolet light of low intensity is shone onto the zinc and it is observed that the leaf of the electroscope collapse. This allows us to conclude that the negative charge on the plate decreased as electrons were ejected from the metal when the ultraviolet light was incident on the plate.

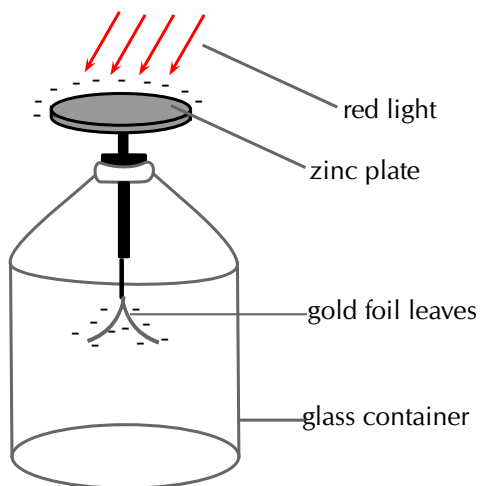



Figure 12.3: Red light incident on the zinc plate of an electroscope.

See video: 27Z4 at www.everythingscience.co.za

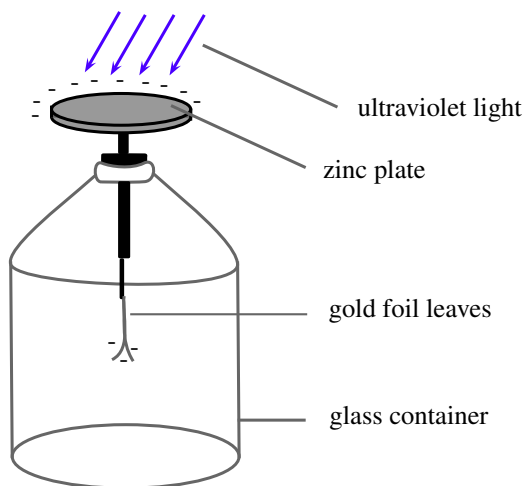



Figure 12.4: Ultraviolet light incident on the zinc plate of an electroscope.

See video: 27Z5 at www.everythingscience.co.za

The work function is different for different elements. The smaller the work function, the easier it is for electrons to be emitted from the metal. Metals with low work functions make good conductors. This is because the electrons are attached less strongly to their surroundings and can move more easily through these materials. This reduces the resistance of the material to the flow of current i.e. it conducts well. Table 12.1 shows the work functions for a range of elements.

| Element | Work Function (J) |
|---|---|
| Aluminium | $6,9 \times 10^{-19}$ |
| Beryllium | $8,0 \times 10^{-19}$ |
| Calcium | $4,6 \times 10^{-19}$ |
| Copper | $7,5 \times 10^{-19}$ |
| Gold | $8,2 \times 10^{-19}$ |
| Lead | $6,9 \times 10^{-19}$ |
| Silicon | $1,8 \times 10^{-19}$ |
| Silver | $6,9 \times 10^{-19}$ |
| Sodium | $3,7 \times 10^{-19}$ |

Table 12.1: Work functions of selected elements determined from the photoelectric effect. (From the *Handbook of Chemistry and Physics.*)

## Units of energy ESCQN

When dealing with calculations at a small scale (like at the level of electrons) it is more convenient to use different units for energy rather than the joule (J). We define a unit called the electron-volt (eV) as the kinetic energy gained by an electron passing through a potential difference of one volt. $E = q \times V$ where q is the charge of the electron and V is the potential difference applied. The charge of 1 electron is $1,6 \times 10^{-19}$ C, so 1 eV

is calculated to be: $1\text{ eV} = \left(1{,}6 \times 10^{-19}\text{ C} \times 1\text{ V}\right) = 1{,}6 \times 10^{-19}\text{ J}$. You can see that $1{,}6 \times 10^{-19}$ J is a very small amount of energy and so using electron-volts (eV) at this level is easier. Hence, $1\text{ eV} = 1{,}6 \times 10^{-19}$ J which means that $1\text{ J} = 6{,}241 \times 10^{18}$ eV.

**Activity: Demonstration of the photoelectric effect**

We can set up an experiment similar to the one used originally to study the photoelectric effect. The experiment allows us to measure the number of electrons emitted and the maximum kinetic energy of the ejected electrons.

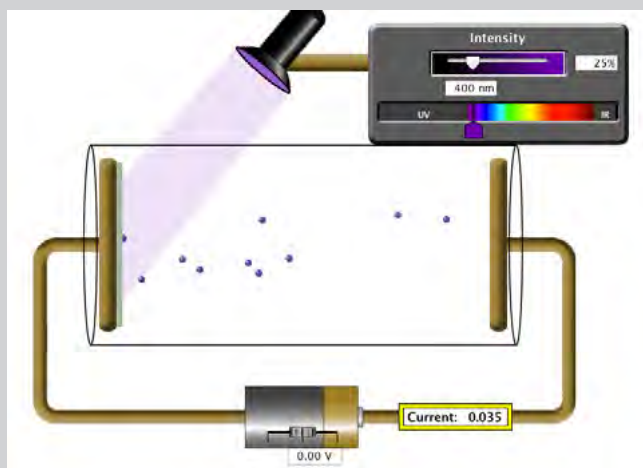



Figure 12.5: Photoelectric effect apparatus

In the diagram of the Photoelectric Effect Apparatus, an ammeter allows for a current to be measured. Measuring the current allows us to deduce information about the number of electrons emitted and the kinetic energy of the ejected electrons.

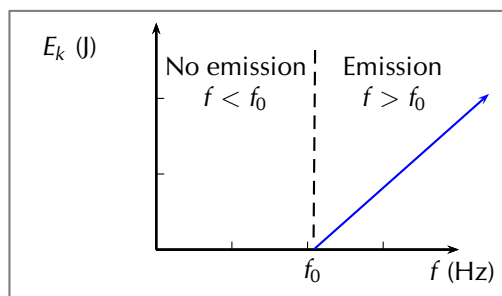
In the diagram, notice that the potential difference supplied by the battery is zero and yet a current is still measured on the ammeter. This is due to the incoming photons having sufficient frequency and hence energy greater than the work function to eject electrons. The ejected electrons travel across the evacuated space and allow for a current to be measured in the circuit.

**Remember**, photon energy is related to frequency while intensity is related to the number of photons.

See simulation: 27Z6 at www.everythingscience.co.za

It is useful to observe the photoelectric effect equation represented graphically. It can be seen from the graph that $E_k$ is plotted on the $y-$axis and $f$ is plotted on the $x-$axis. Using the straight line equation, $y = mx + c$, we can identify

$$E_{k\text{ max}} = hf - W_0$$

$$\underbrace{E_{k\text{ max}}}_{y} = h\underbrace{f}_{x} - hf_0$$

This allows us to conclude that the slope of the graph $m$ is Planck's constant $h$. Also, the $x$ intercept is the cut-off frequency $f_0$.

**Worked example 1: The photoelectric effect using silver**

***QUESTION***

Ultraviolet radiation with a wavelength of 250 nm is incident on a silver foil (work function $W_0 = 6{,}9 \times 10^{-19}$ J). What is the maximum kinetic energy of the emitted electrons?

***SOLUTION***

**Step 1: Determine what is required and how to approach the problem**

We need to determine the maximum kinetic energy of an electron ejected from a silver foil by ultraviolet radiation.

The photoelectric effect tells us that:

$$E_{k\text{ max}} = E_{\text{photon}} - W_0$$

$$E_{k\text{ max}} = h\frac{c}{\lambda} - W_0$$

We also have:

- Work function of silver: $W_{0\text{ silver}} = 6{,}9 \times 10^{-19}$ J
- UV radiation wavelength $= 250$ nm $= 250 \times 10^{-9}$ m $= 2{,}50 \times 10^{-7}$ m
- Planck's constant: $h = 6{,}63 \times 10^{-34}$ m$^2$·kg·s$^{-1}$
- Speed of light: $c = 3 \times 10^8$ m·s$^{-1}$

**Step 2: Solve the problem**

$$\begin{aligned} E_k &= \frac{hc}{\lambda} - W_{0\text{ silver}} \\ &= \left[6{,}63 \times 10^{-34} \times \frac{3 \times 10^8}{2{,}5 \times 10^{-7}}\right] - 6{,}9 \times 10^{-19} \\ &= 1{,}06 \times 10^{-19}\text{ J} \end{aligned}$$

The maximum kinetic energy of the emitted electron will be $1{,}06 \times 10^{-19}$ J.

## Worked example 2: The photoelectric effect using gold

### *QUESTION*

If we were to shine the same ultraviolet radiation ($f = 1{,}2 \times 10^{15}$ Hz) on a gold foil (work function $= 8{,}2 \times 10^{-19}$ J ) would any electrons be emitted from the surface of the gold foil?

### *SOLUTION*

**Step 1: Calculate the energy of the incident photons**

For the electrons to be emitted from the surface, the energy of each photon needs to be *greater* than the work function of the material.

$$\begin{aligned} E_{\text{photon}} &= hf \\ &= 6{,}63 \times 10^{-34} \times 1{,}2 \times 10^{15} \\ &= 7{,}96 \times 10^{-19}\ \text{J} \end{aligned}$$

Therefore each photon of ultraviolet light has an energy of $7{,}96 \times 10^{-19}$ J.

**Step 2: Write down the work function for gold.**

$$W_{0\ \text{gold}} = 8{,}92 \times 10^{-19}\ \text{J}$$

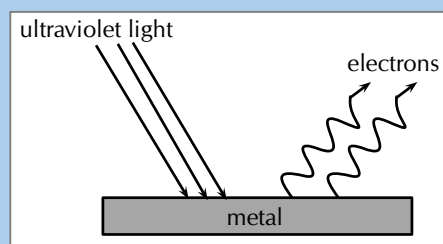
**Step 3: Is the energy of the photons greater or smaller than the work function?**

$$\begin{aligned} 7{,}96 \times 10^{-19}\ \text{J} &< 8{,}92 \times 10^{-19}\ \text{J} \\ E_{\text{photons}} &< W_{0\ \text{gold}} \end{aligned}$$

Since the energy of each photon is less than the work function of gold, the photons do not have enough energy to knock electrons out of the gold. No electrons would be emitted from the gold foil.

## Worked example 3: Photoelectric effect [NSC 2011 Paper 1]

### *QUESTION*

A metal surface is illuminated with ultraviolet light of wavelength 330 nm. Electrons are emitted from the metal surface. The minimum amount of energy required to emit an electron from the surface of this metal is $3{,}5 \times 10^{-19}$ J.

1. Name the phenomenon illustrated above. (1 mark)
2. Give ONE word or term for the underlined sentence in the above paragraph. (1 mark)
3. Calculate the frequency of the ultraviolet light. (4 marks)
4. Calculate the kinetic energy of a photoelectron emitted from the surface of the metal when the ultraviolet light shines on it. (4 marks)
5. The intensity of the ultraviolet light illuminating the metal is now increased. What effect will this change have on the following:
   a) Kinetic energy of the emitted photoelectrons (Write down only INCREASES, DECREASES or REMAINS THE SAME.) (1 mark)

b) Number of photoelectrons emitted per second (Write down only INCREASES, DECREASES or REMAINS THE SAME.) (1 mark)

6. Overexposure to sunlight causes damage to skin cells.

a) Which type of radiation in sunlight is said to be primarily responsible for this damage? (1 mark)

b) Name the property of this radiation responsible for the damage. (1 mark)

**[TOTAL: 14 marks]**

***SOLUTION***

**Question 1:** Photo-electric effect (1 mark)

**Question 2:** Work function (1 mark)

**Question 3**

$$\begin{aligned} c &= f\lambda \\ 3 \times 10^{8} &= f(330 \times 10^{-9}) \\ \therefore f &= 9,09 \times 10^{14}\ \text{Hz} \end{aligned}$$

(4 marks)

**OR**

$$\begin{aligned} E &= \frac{hc}{\lambda} \\ &= \frac{(6,63 \times 10^{-34})(3 \times 10^{8})}{(330 \times 10^{-9})} \\ &= 6,03 \times 10^{-19}\ \text{J} \end{aligned}$$

$$\begin{aligned} E &= hf \\ 6,03 \times 10^{-19} &= (6,63 \times 10^{-34})f \\ \therefore f &= 9,09 \times 10^{14}\ \text{Hz} \end{aligned}$$

**Question 4**

**Option 1:**

$$\begin{aligned} E &= W_o + K \\ \frac{hc}{\lambda} &= W_o + K \\ \therefore \frac{(6,63 \times 10^{-34})(3 \times 10^{8})}{330 \times 10^{-9}} &= 3,5 \times 10^{-19} + K \\ \therefore K &= 2,53 \times 10^{-19}\ \text{J} \end{aligned}$$

**Option 2:**

$$\begin{aligned} E &= W_o + K \\ hf &= W_o + K \\ \therefore (6,63 \times 10^{-34})(9,09 \times 10^{14} &= 3,5 \times 10^{-19} + K \\ \therefore K &= 2,53 \times 10^{-19}\ \text{J} \end{aligned}$$

(4 marks)

**Question 5.1:** Remains the same. (1 mark)

**Question 5.2:** Increases (1 mark)

**Question 6.1:** Ultraviolet radiation (1 mark)

**Question 6.2:** High energy or high frequency (1 mark)

**[TOTAL: 12 marks]**

The generation of electricity using solar cells isn't due to the photoelectric effect but is similar in nature. Photons in sunlight hit the solar panel and are absorbed by semiconducting materials, such as silicon.

Electrons (negatively charged) are knocked loose from their atoms, allowing them to flow through the material to produce electricity. This is called the photovoltaic effect. The photovoltaic effect was first observed by French physicist Antoine E. Becquerel in 1839.

Due to the special composition of solar cells, the electrons are only allowed to move in a single direction. An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity.

**Exercise 12 – 1: The photoelectric effect**

1. Describe the photoelectric effect.
2. List two reasons why the observation of the photoelectric effect was significant.
3. Refer to 12.1: If I shine ultraviolet light with a wavelength of 288 nm onto some aluminium foil, what would the kinetic energy of the emitted electrons be?
4. I shine a light of an unknown wavelength onto some silver foil. The light has only enough energy to eject electrons from the silver foil but not enough to give them kinetic energy. (Refer to 12.1 when answering the questions below:)
   a) If I shine the same light onto some copper foil, would electrons be ejected?
   b) If I shine the same light onto some silicon, would electrons be ejected?
   c) If I increase the intensity of the light shining on the silver foil, what happens?
   d) If I increase the frequency of the light shining on the silver foil, what happens?
5. The following results were obtained from a photoelectric effect experiment.

| $f$ ($\times 10^{15}$ Hz) | $E_k$ ($\times 10^{-19}$ J) |
|---|---|
| 0.60 | 0.24 |
| 0.80 | 1.59 |
| 1.00 | 2.89 |
| 1.20 | 4.20 |
| 1.40 | 5.55 |
| 1.60 | 6.89 |

   a) Plot a graph of $E_k$ on the $y$ axis and $f$ on the x axis
   b) Calculate the gradient of the graph.
   c) The metal used in the experiment is Sodium which has a work function of $3,7 \times 10^{-19}$. Calculate the cut-off frequency for sodium.
   d) Determine the $x$ intercept. Compare your $x$ intercept value with the cut-off frequency you calculated.
   e) If the sodium metal was replaced with another metal with double the work function, sketch on the same graph for sodium, the result you would expect to obtain.

6. More questions. Sign in at Everything Science on-line and click 'Practice Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27Z7 2. 27Z8 3. 27Z9 4. 27ZB 5. 27ZC

## 12.3 Emission and absorption spectra ESCQR

### Emission spectra ESCQS

You have learnt previously about the structure of an atom. The electrons surrounding the atomic nucleus are arranged in a series of levels of increasing energy. Each element has a unique number of electrons in a unique configuration therefore each element has its own distinct set of energy levels. This arrangement of energy levels serves as the atom's unique fingerprint.

In the early 1900s, scientists found that a liquid or solid heated to high temperatures would give off a broad range of colours of light. However, a gas heated to similar temperatures would emit light only at certain specific wavelengths (colours). The reason for this observation was not understood at the time.

Scientists studied this effect using a discharge tube.

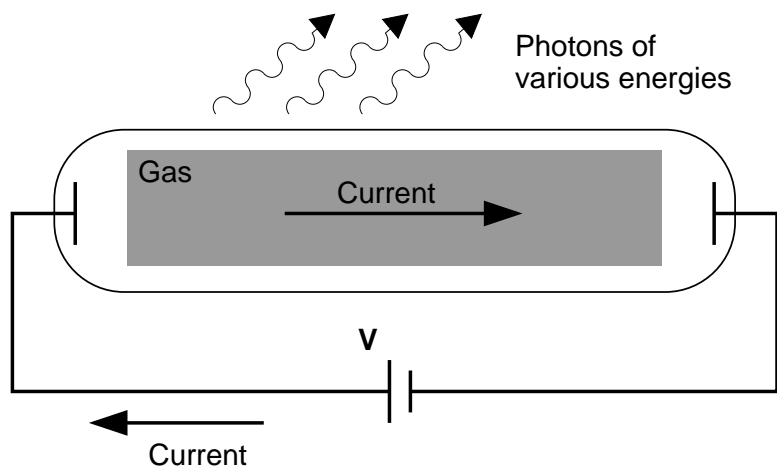



Figure 12.6: Diagram of a discharge tube. The tube is filled with a gas. When a high enough voltage is applied across the tube, the gas ionises and acts like a conductor, allowing a current to flow through the circuit. The current excites the atoms of the ionised gas. When the atoms fall back to their ground state, they emit photons to carry off the excess energy.

A discharge tube (shown in Figure 12.6) is a gas-filled, glass tube with a metal plate at both ends. If a large enough voltage difference is applied between the two metal

plates, the gas atoms inside the tube will absorb enough energy to make some of their electrons come off, i.e. the gas atoms are ionised. These electrons start moving through the gas and create a current, which raises some electrons in other atoms to higher energy levels. Then as the electrons in the atoms fall back down, they emit electromagnetic radiation (light). The amount of light emitted at different wavelengths, called the **emission spectrum**, is shown for a discharge tube filled with hydrogen gas in 12.7 below. Only certain wavelengths (i.e. colours) of light are seen, as shown by the lines in the picture.

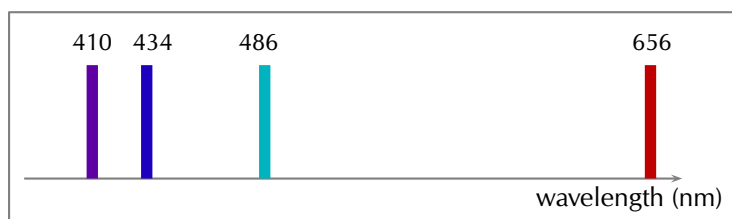



Figure 12.7: Diagram of the emission spectrum of hydrogen in the visible spectrum. Four lines are visible, and are labelled with their wavelengths. The three lines in the 400–500 nm range are in the blue part of the spectrum, while the higher line (656 nm) is in the red/orange part.

Eventually, scientists realised that these lines come from photons of a specific energy, emitted by electrons making transitions between specific energy levels of the atom. Figure 12.8 shows an example of this happening. When an electron in an atom falls from a higher energy level to a lower energy level, it emits a photon to carry off the extra energy. This photon's energy is equal to the energy difference between the two energy levels ($\Delta E$).

$$\Delta E_{\text{electron}} = E_f - E_i$$

As we previously discussed, the frequency of a photon is related to its energy through the equation $E = hf$. Since a specific photon frequency (or wavelength) gives us a specific colour, we can see how each coloured line is associated with a specific transition.

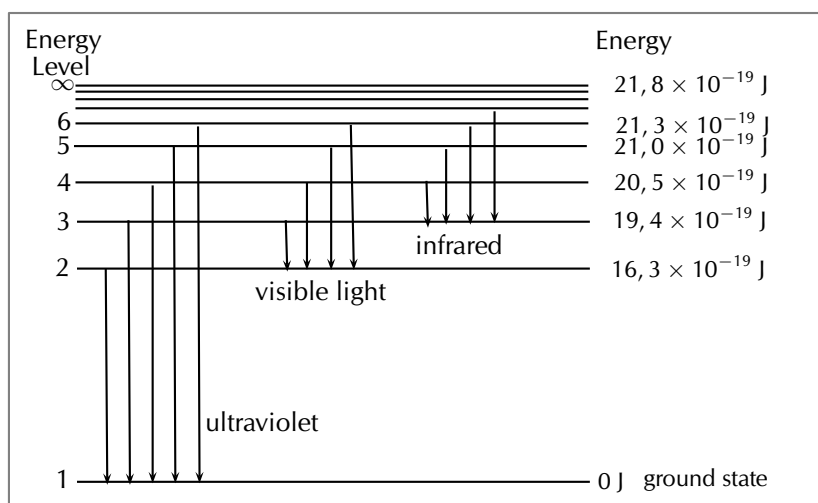
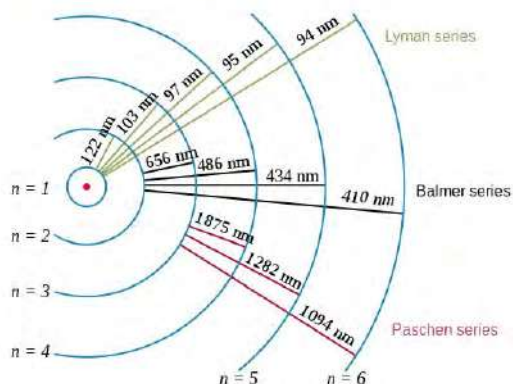



Figure 12.8: In the first diagram are shown some of the electron energy levels for the hydrogen atom. The arrows show the electron transitions from higher energy levels to lower energy levels. The energies of the emitted photons are the same as the energy difference between two energy levels. You can think of absorption as the opposite process. The arrows would point upwards and the electrons would jump up to higher levels when they absorb a photon of the right energy. The second representation shows the wavelengths of the light that is emitted for the the various transitions. The transistions are grouped into a series based on the lowest level involved in the transition.

Visible light is not the only kind of electromagnetic radiation emitted. More energetic or less energetic transitions can produce ultraviolet or infrared radiation. However, because each atom has its own distinct set of energy levels (its fingerprint!), each atom has its own distinct emission spectrum.

## Absorption spectra ESCQT

Atoms do not only emit photons; they also absorb photons. If a photon hits an atom and the energy of the photon is the same as the gap between two electron energy levels in the atom, then the electron in the lower energy level can absorb the photon and jump up to the higher energy level. If the photon energy does not correspond to the difference between two energy levels then the photon will not be absorbed (it can still be scattered).

Using this effect, if we have a source of photons of various energies we can obtain the **absorption spectra** for different materials. To get an absorption spectrum, just shine white light on a sample of the material that you are interested in. White light is made up of all the different wavelengths of visible light put together. In the absorption spectrum there will be gaps. The gaps correspond to energies (wavelengths) for which there is a corresponding difference in energy levels for the particular element.

The absorbed photons show up as black lines because the photons of these wavelengths have been absorbed and do not show up. Because of this, the absorption spectrum is the exact *inverse* of the emission spectrum. Look at the two figures below. In Figure 12.9 you can see the line emission spectrum of hydrogen. Figure 12.10 shows the absorption spectrum. It is the exact opposite of the emission spectrum! Both emission and absorption techniques can be used to get the same information about the energy levels of an atom.

Figure 12.9: *Emission* spectrum of Hydrogen.

Figure 12.10: *Absorption* spectrum of Hydrogen.

The dark lines correspond to the frequencies of light that have been absorbed by the gas. As the photons of light are absorbed by electrons, the electrons move into higher energy levels. This is the opposite process of emission.

The dark lines, absorption lines, correspond to the frequencies of the emission spectrum of the same element. The amount of energy absorbed by the electron to move into a higher level is the same as the amount of energy released when returning to the original energy level.

**Worked example 4: Absorption**

***QUESTION***

I have an unknown gas in a glass container. I shine a bright white light through one side of the container and measure the spectrum of transmitted light. I notice that there is a black line (*absorption* line) in the middle of the visible red band at 642 nm. I have a hunch that the gas might be hydrogen. If I am correct, between which 2 energy levels does this transition occur? (Hint: look at Figure 12.8 and the transitions which are in the visible part of the spectrum.)

***SOLUTION***

**Step 1: What is given and what needs to be done?**

We have an absorption line at 642 nm. This means that the substance in the glass container absorbed photons with a wavelength of 642 nm. We need to calculate which 2 energy levels of hydrogen this transition would correspond to. Therefore we need to know what energy the absorbed photons had.

**Step 2: Calculate the energy of the absorbed photons**

$$\begin{aligned} E &= \frac{hc}{\lambda} \\ &= \frac{\left(6{,}63 \times 10^{-34}\right) \times \left(3 \times 10^{8}\right)}{642 \times 10^{-9}} \\ &= 3{,}1 \times 10^{-19}\ \text{J} \end{aligned}$$

The absorbed photons had an energy of $3{,}1 \times 10^{-19}$ J.

**Step 3: Find the energy of the transitions resulting in radiation at visible wavelengths**

Figure 12.8 shows various energy level transitions. The transitions related to visible wavelengths are marked as the transitions beginning or ending on Energy Level 2. Let us find the energy of those transitions and compare with the energy of the absorbed photons we have just calculated.

Energy of transition (absorption) from Energy Level 2 to Energy Level 3:

$$\begin{aligned}\Delta E_{electron} &= E_{2,3} = E_2 - E_3 \\ &= 16{,}3 \times 10^{-19} - 19{,}4 \times 10^{-19} \\ &= -3{,}1 \times 10^{-19}\text{ J}\end{aligned}$$

Therefore the energy of the photon that an electron must absorb to jump from Energy Level 2 to Energy Level 3 is $3{,}1 \times 10^{-19}$ J. (NOTE: The minus sign means that *absorption* is occurring.)

This is the same energy as the photons which were absorbed by the gas in the container! Therefore, since the transitions of all elements are unique, we can say that the gas in the container is hydrogen. The transition is absorption of a photon between Energy Level 2 and Energy Level 3.

**IMPORTANT!**

---

The energy of the photon does not correspond to the energy of an energy level, it corresponds to the **difference** in energy between two energy levels.

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## Applications of emission and absorption spectra ESCQV

The study of spectra from stars and galaxies in astronomy is i called *spectroscopy*. Spectroscopy is a tool widely used in astronomy to learn different things about astronomical objects.

### Identifying elements in astronomical objects using their spectra

Measuring the spectrum of light from a star can tell astronomers what the star is made of. Since each element emits or absorbs light only at particular wavelengths, astronomers can identify what elements are in the stars from the lines in their spectra. From studying the spectra of many stars we know that there are many different types of stars which contain different elements and in different amounts.

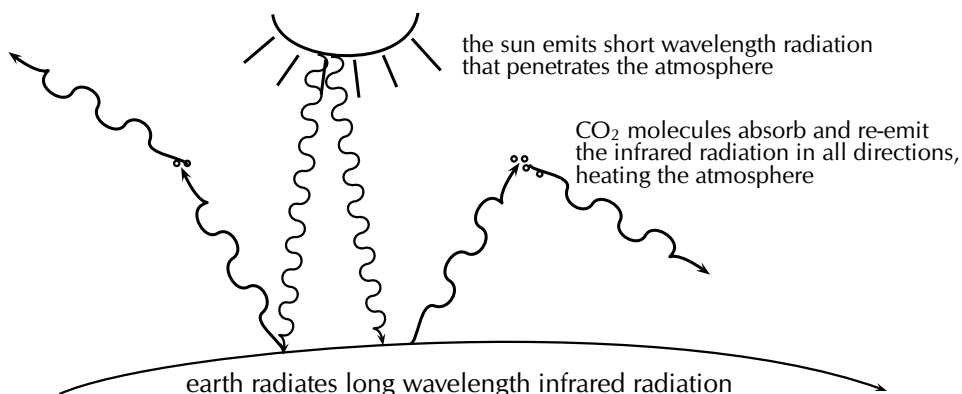
### Determining velocities of galaxies using spectroscopy

You have already learnt in Chapter 6 about the Doppler effect and how the frequency (and wavelength) of sound waves changes depending on whether the object emitting the sound is moving *towards* or *away* from you. The same thing happens to electromagnetic radiation (light). If the object emitting the light is moving *towards* us, then the wavelength of the light appears shorter (called **blueshifted**). If the object is moving *away* from us, then the wavelength of its light appears stretched out (called **redshifted**).

The Doppler effect affects the spectra of objects in space depending on their motion relative to us on the earth. For example, the light from a distant galaxy that is moving away from us at some velocity will appear redshifted. This means that the emission and absorption lines in the galaxy's spectrum will be shifted to a longer wavelength (lower frequency). Knowing where each line in the spectrum would normally be if the galaxy was not moving and comparing it to the redshifted position, allows astronomers to precisely measure the velocity of the galaxy relative to the Earth.

### Global warming and greenhouse gases

The sun emits radiation (light) over a range of wavelengths that are mainly in the visible part of the spectrum. Radiation at these wavelengths passes through the gases of the

atmosphere to warm the land and the oceans below. The warm earth then radiates this heat at longer infrared wavelengths. Carbon dioxide (one of the main greenhouse gases) in the atmosphere has energy levels that correspond to the infrared wavelengths that allow it to absorb the infrared radiation. It then also emits at infrared wavelengths in all directions. This effect stops a large amount of the infrared radiation from getting out of the atmosphere, which causes the atmosphere and the earth to heat up. More radiation is coming in than is getting back out.

So increasing the amount of greenhouse gases in the atmosphere increases the amount of trapped infrared radiation and therefore the overall temperature of the earth. The earth is a very sensitive and complicated system upon which life depends and changing the delicate balances of temperature and atmospheric gas content may have disastrous consequences if we are not careful.

**Exercise 12 – 2: Emission and absorption spectra**

1. Explain how atomic emission spectra arise and how they relate to each element on the periodic table.
2. How do the lines on the atomic spectrum relate to electron transitions between energy levels?
3. Explain the difference between atomic absorption and emission spectra.
4. Describe how the absorption and emission spectra of the gases in the atmosphere give rise to the Greenhouse Effect.
5. What colour is the light emitted by hydrogen when an electron makes the transition from energy level 5 down to energy level 2? (Use 12.8 to find the energy of the released photon.)
6. I have a glass tube filled with hydrogen gas. I shine white light onto the tube. The spectrum I then measure has an absorption line at a wavelength of 474 nm. Between which two energy levels did the transition occur? (Use 12.8 in solving the problem.)
7. More questions. Sign in at Everything Science on-line and click 'Practice Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27ZD 2. 27ZF 3. 27ZG 4. 27ZH 5. 27ZK
7. 27ZM

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## 12.4 Chapter summary ESCQW

See presentation: 27ZN at www.everythingscience.co.za

- The photoelectric effect is the process whereby an electron is emitted by a substance when light shines on it.
- A substance has a work function which is the minimum energy needed to emit an electron from the metal. The frequency of light whose photons correspond exactly to the work function is known as the cut-off frequency.

$$E = W_0 + E_{k\ \text{max}}$$
$$E_{k\ \text{max}} = hf - W_0$$

- The number of electrons ejected increases with the intensity of the incident light.
- The photoelectric effect illustrates the particle nature of light and establishes the quantum theory.
- Emission spectra are formed when certain frquencies of light are emitted by a gas, as a result of electrons in the atmoms dropping from higher to lower energy levels. The pattern of the spectra is charactersistic of the specific gas.
- Absorption spectra are formed when certain frequencies of light are absorbed by a material. These photons are absorbed when their energy is exactly the correct amount to raise an electron from one energy level to another.

| Physical Quantities | | |
|---|---|---|
| **Quantity** | **Unit name** | **Unit symbol** |
| Energy ($E$) | joule | J |
| Work function ($W_0$) | joule | J |
| Frequency ($f$) | hertz | Hz |
| Wavelength ($\lambda$) | metre | m |

Table 12.2: Units used in **optical phenomena and properties of matter**.

**Exercise 12 – 3:**

1. Calculate the energy of a photon of red light with a wavelength of 400 nm.
2. Will ultraviolet light with a wavelength of 990 nm be able to emit electrons from a sheet of calcium with a work function of 2,9 eV?
3. More questions. Sign in at Everything Science on-line and click 'practise'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27ZP 2. 27ZQ

# CHAPTER 13

## *Electrochemical reactions*

We use batteries throughout our day-to-day lives. Cell phones use lithium-ion batteries, cars use lead-acid batteries (Figure 13.1 (left)), while silver-oxide batteries (Figure 13.1 (top right)) are used in watches. Some batteries are rechargeable (Figure 13.1 (bottom right)), while others cannot be recharged and have to be thrown away.

Figure 13.1: A car battery, watch batteries and rechargeable AA batteries.

A battery consists of multiple **electrochemical cells**. And within each cell there are **electrochemical reactions** taking place. This can be seen in the *lemon battery* experiment shown in Figure 13.2. Each lemon is a cell in the battery, which consists of three lemon cells. The reactions the copper and zinc undergo in the lemons are electrochemical reactions, and a current is produced.

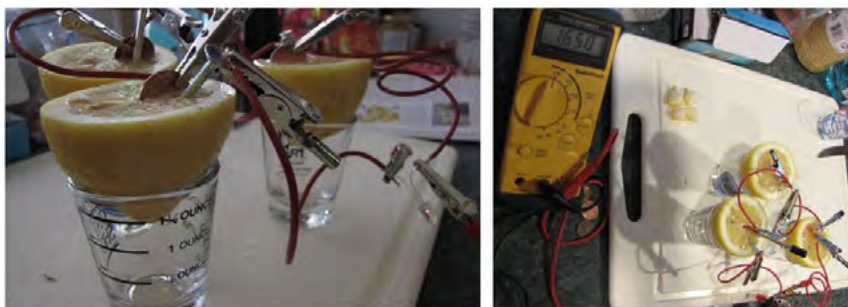



Figure 13.2: A current is produced by connecting lemons with zinc and copper metal. The reactions taking place here are electrochemical reactions.

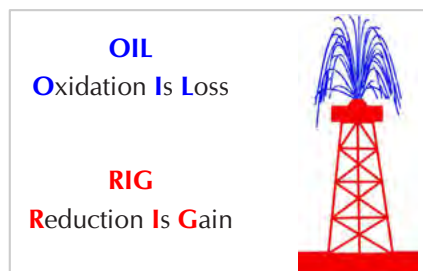
Electrochemical reactions, and electrochemical cells are covered in this chapter. Before going into any more detail however, it is important to revise oxidation and reduction, as well as redox reactions and how to balance them, as these concepts are very important in electrochemistry.

## 13.1 Revision of oxidation and reduction ESCQX

You should remember the terms *oxidation* and *reduction* from Grade 11:

- **Oxidation** involves a **loss of electrons**
- **Reduction** involves a **gain of electrons**.

An easy way to remember this is:

In both oxidation and reduction a **transfer of electrons** is involved resulting in a change in the oxidation state of the elements.

- An element or compound that **loses** electrons is **oxidised**.
  e.g. $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$
  As it loses electrons it *gives* them away to another element or compound and the element or compound it gives the electrons to is **reduced**.
  This makes the compound or element which loses electrons a **reducing agent**.
- An element or compound that **gains** electrons is **reduced**.
  e.g. $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$
  As it gains electrons it *takes* them away from another element or compound and the element or compound it takes them from is **oxidised**.
  This makes the compound or element which gains electrons an **oxidising agent**.

**Exercise 13 – 1: Oxidation and reduction**

1. Define the following terms:
   a) oxidation b) reduction c) oxidising agent d) reducing agent
2. In each of the following reactions say whether the reactant **iron species** (Fe, $Fe^{2+}$, $Fe^{3+}$) is oxidised or reduced.
   a) $Fe(s) \rightarrow Fe^{2+}(aq) + 2e^-$
   b) $Fe^{3+}(aq) + e^- \rightarrow Fe^{2+}(aq)$
   c) $Fe_2O_3(s) + 3CO(g) \rightarrow 2Fe(s) + 3CO_2(g)$
   d) $Fe^{2+}(aq) \rightarrow Fe^{3+}(aq) + e^-$
   e) $Fe_2O_3(s) + 2Al(s) \rightarrow Al_2O_3(s) + 2Fe(s)$
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27ZR 2. 27ZS

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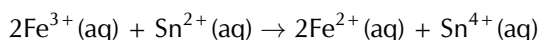
## 13.2 Writing redox and half-reactions ESCQY

### Redox reactions and half-reactions ESCQZ

Remember from Grade 11 that oxidation and reduction occur simultaneously in a **redox** reaction. The reactions taking place in electrochemical cells are redox reactions. Two questions should be asked to determine if a reaction is a redox reaction:

- Is there a compound or atom being oxidised?
- Is there a compound or atom being reduced?

If the answer to both of these questions is yes, then the reaction is a redox reaction. For example, this reaction is a redox reaction:

$2Fe^{3+}(aq) + Sn^{2+}(aq) \rightarrow 2Fe^{2+}(aq) + Sn^{4+}(aq)$

You can write a redox reaction as two **half-reactions**, one showing the reduction process, and one showing the oxidation process. $Fe^{3+}$ is gaining an electron to become $Fe^{2+}$. **Iron** is therefore being **reduced** and **tin** is the **reducing agent** (causing iron to be reduced). The **reduction half-reaction** is:

$\mathbf{Fe^{3+}(aq) + e^{-} \rightarrow Fe^{2+}(aq)}$

$Sn^{2+}$ is losing two electrons to become $Sn^{4+}$. **Tin** is therefore being **oxidised** and **iron** is the **oxidising agent** (causing tin to be oxidised). The **oxidation half-reaction** is:

$\mathbf{Sn^{2+}(aq) \rightarrow Sn^{4+}(aq) + 2e^{-}}$

Notice that in the **overall** reaction the reduction half-reaction is multiplied by two. This is so that the number of electrons gained in the reduction half-reaction match the number of electrons lost in the oxidation half-reaction.

## Balancing redox reactions ESCR2

Half-reactions can be used to balance redox reactions. We are going to use some worked examples to help explain the method.

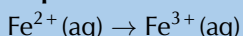
### Worked example 1: Balancing redox reactions

***QUESTION***

Chlorine gas oxidises $Fe^{2+}$ ions to $Fe^{3+}$ ions. In the process, chlorine is reduced to chloride ions. Write a balanced equation for this reaction.

***SOLUTION***

**Step 1: Write down the unbalanced oxidation half-reaction**

$Fe^{2+}(aq) \rightarrow Fe^{3+}(aq)$

**Step 2: Balance the number of atoms on both sides of the equation**

There is one iron atom on the left and one on the right, so no additional atoms need to be added.

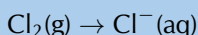
**Step 3: Once the atoms are balanced, check that the *charges* balance**

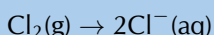
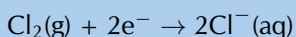
The charge on the left of the equation is $+2$, but the charge on the right is $+3$. Therefore, one electron must be added to the right hand side so that the charges balance. The half-reaction is now:

$Fe^{2+}(aq) \rightarrow Fe^{3+}(aq) + e^{-}$

**Step 4: Repeat steps 1 - 3 with the reduction half-reaction**

The unbalanced reduction half-reaction is:

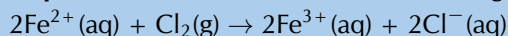
$Cl_2(g) \rightarrow Cl^{-}(aq)$

The atoms don't balance, so we need to multiply the right hand side by two to fix this.

$Cl_2(g) \rightarrow 2Cl^{-}(aq)$

Two electrons must be added to the left hand side to balance the charges.

$Cl_2(g) + 2e^{-} \rightarrow 2Cl^{-}(aq)$

**Step 5: Compare the number of electrons in each equation**

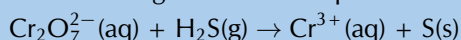
Multiply each half-reaction by a suitable number so that the number of electrons released (oxidation) is equal to the number of electrons accepted (reduction).

oxidation half-reaction: $\times$**2**: $2Fe^{2+}(aq) \rightarrow 2Fe^{3+}(aq) + \mathbf{2e^-}$
reduction half-reaction: $\times$**1**: $Cl_2(g) + \mathbf{2e^-} \rightarrow 2Cl^-(aq)$

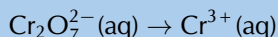
**Step 6: Combine the two half-reactions to get a final equation for the overall reaction**
$2Fe^{2+}(aq) + Cl_2(g) \rightarrow 2Fe^{3+}(aq) + 2Cl^-(aq)$

**Step 7: Do a final check to make sure that the equation is balanced**
We check the number of atoms and the charges and find that the equation is balanced.

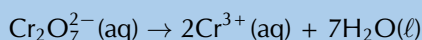
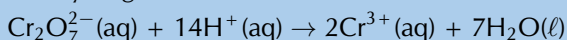
**Worked example 2: Balancing redox reactions in an acid medium**

***QUESTION***

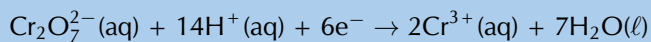
The following reaction takes place in an acid medium:
$Cr_2O_7^{2-}(aq) + H_2S(g) \rightarrow Cr^{3+}(aq) + S(s)$
Write a balanced equation for this reaction.

***SOLUTION***

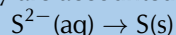
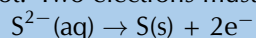
**Step 1: Write down the unbalanced reduction half-reaction**
In $Cr_2O_7^{2-}$ chromium exists as $Cr^{6+}$. It becomes $Cr^{3+}$. Therefore electrons are gained, this is the reduction half-reaction:

$$Cr_2O_7^{2-}(aq) \rightarrow Cr^{3+}(aq)$$

**Step 2: Balance the number of atoms on both sides of the equation**
We need to multiply the right side by two so that the number of Cr atoms will balance. In an acid medium there are water molecules and $H^+$ ions in the solution, so these can be used to balance the equation.
To balance the oxygen atoms, we will need to add water molecules to the right hand side:

$$Cr_2O_7^{2-}(aq) \rightarrow 2Cr^{3+}(aq) + 7H_2O(\ell)$$

Now the oxygen atoms balance but the hydrogens don't. Because the reaction takes place in an acid medium, we can add hydrogen ions to the left side.

$$Cr_2O_7^{2-}(aq) + 14H^+(aq) \rightarrow 2Cr^{3+}(aq) + 7H_2O(\ell)$$

**Step 3: Once the atoms are balanced, check that the *charges* balance**
The charge on the left of the equation is $(-2 + 14) = +12$, but the charge on the right is $+6$. Therefore, six electrons must be added to the left hand side so that the charges balance. This makes sense as electrons are gained in the reduction half-reaction. The half-reaction is now:

$$Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6e^- \rightarrow 2Cr^{3+}(aq) + 7H_2O(\ell)$$

**Step 4: Repeat steps 1 - 3 with the oxidation half-reaction**
The unbalanced oxidation half-reaction is: $H_2S(g) \rightarrow S(s)$

However, you can ignore the $H^+$ in $H_2S$ as they are accounted for by the acid medium and the reduction half-reaction. $S^{2-}(aq) \rightarrow S(s)$

The atoms balance, however the charges do not. Two electrons must be added to the right hand side of the equation. $S^{2-}(aq) \rightarrow S(s) + 2e^-$

**Step 5: Compare the number of electrons in each equation**

Multiply each half-reaction by a suitable number so that the number of electrons released (oxidation) is equal to the number of electrons accepted (reduction).

oxidation half-reaction: $\times\mathbf{3}$: $3S^{2-}(aq) \rightarrow 3S(s) + \mathbf{6e^-}$

reduction half-reaction: $\times\mathbf{1}$: $Cr_2O_7^{2-}(aq) + 14H^+(aq) + \mathbf{6e^-} \rightarrow 2Cr^{3+}(aq) + 7H_2O(\ell)$

**Step 6: Combine the two half-reactions to get a final equation for the overall reaction**

$Cr_2O_7^{2-}(aq) + 14H^+(aq) + 3S^{2-}(aq) \rightarrow 3S(s) + 2Cr^{3+}(aq) + 7H_2O(\ell)$

However, $H_2S(g)$ is the reactant, so it would be better to write:

$Cr_2O_7^{2-}(aq) + 8H^+(aq) + 3H_2S(g) \rightarrow 3S(s) + 2Cr^{3+}(aq) + 7H_2O(\ell)$

**Step 7: Do a final check to make sure that the equation is balanced**

We check the number of atoms and the charges and find that the equation is balanced.

**Worked example 3: Balancing redox reactions in an alkaline medium**

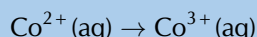
***QUESTION***

The complex ion hexaamminecobalt(II) ($Co(NH_3)_6^{2+}$) is oxidised by hydrogen peroxide to form the hexaamminecobalt(III) ion ($Co(NH_3)_6^{3+}$). Write a balanced equation for this reaction.

***SOLUTION***

**Step 1: Write down the unbalanced oxidation half-reaction**

Ammonia ($NH_3$) has an oxidation number of 0. Therefore, in $Co(NH_3)_6^{2+}$ cobalt exists as $Co^{2+}$. In $Co(NH_3)_6^{3+}$ cobalt exists as $Co^{3+}$. Electrons are lost and this is the oxidation half-reaction:

$$Co^{2+}(aq) \rightarrow Co^{3+}(aq)$$

**Step 2: Balance the number of atoms on both sides of the equation**

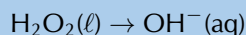
The number of atoms are the same on both sides.

**Step 3: Once the atoms are balanced, check that the *charges* balance**

The charge on the left of the equation is $+2$, but the charge on the right is $+3$. One electron must be added to the right hand side to balance the charges in the equation:

$$Co^{2+} \rightarrow Co^{3+} + e^-$$

**Step 4: Repeat steps 1 - 3 with the reduction half-reaction**

Cobalt is oxidised by hydrogen peroxide, therefore hydrogen peroxide is reduced. Reduction means a gain of electrons. The product of the reduction of $H_2O_2$ in an alkaline medium is $OH^-$:

$$H_2O_2(\ell) \rightarrow OH^-(aq)$$

Next you need to balance the atoms: $H_2O_2(\ell) \rightarrow 2OH^-(aq)$

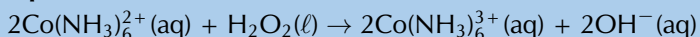
Then you need to balance the charges: $H_2O_2(\ell) + 2e^- \rightarrow 2OH^-(aq)$

**Step 5: Compare the number of electrons in each equation**

Multiply each half-reaction by a suitable number so that the number of electrons released (oxidation) is equal to the number of electrons accepted (reduction):

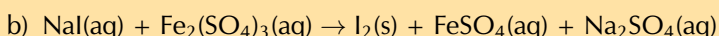
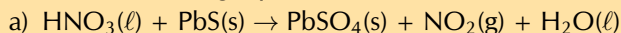
oxidation half-reaction: $\times\mathbf{2}$: $2Co^{2+}(aq) \rightarrow 2Co^{3+}(aq) + \mathbf{2e^-}$

reduction half-reaction: $\times\mathbf{1}$: $H_2O_2(\ell) + \mathbf{2e^-} \rightarrow 2OH^-(aq)$

**Step 6: Combine the two half-reactions, and add in the spectator ions, to get a final equation for the overall reaction**

$2Co(NH_3)_6^{2+}(aq) + H_2O_2(\ell) \rightarrow 2Co(NH_3)_6^{3+}(aq) + 2OH^-(aq)$

**Step 7: Do a final check to make sure that the equation is balanced**

We check the number of atoms and the charges and find that the equation is balanced.

**Exercise 13 – 2: Balancing redox reactions**

1. Balance the following equations:
   a) $HNO_3(\ell) + PbS(s) \rightarrow PbSO_4(s) + NO_2(g) + H_2O(\ell)$
   b) $NaI(aq) + Fe_2(SO_4)_3(aq) \rightarrow I_2(s) + FeSO_4(aq) + Na_2SO_4(aq)$
2. Permanganate(VII) ions ( $MnO_4^-$ ) oxidise hydrogen peroxide ( $H_2O_2$ ) to oxygen gas. The reaction is done in an acid medium. During the reaction, the permanganate(VII) ions are reduced to manganese(II) ions ($Mn^{2+}$ ). Write a balanced equation for the reaction.
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1a. 27ZT 1b. 27ZV 2. 27ZW

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## 13.3 Galvanic and electrolytic cells ESCR3

### Electrochemical reactions ESCR4

In Grade 11, you carried out an experiment to see what happens when zinc granules are added to a solution of copper(II) sulfate.

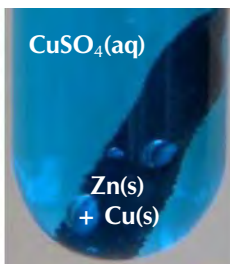
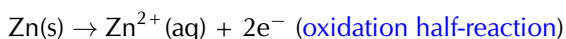
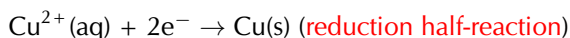
Zn(s) before

Zn(s) + Cu(s) layer after

Figure 13.3: When a sheet of zinc is placed in an aqueous solution of copper(II) sulfate, solid copper forms on the zinc sheet. (Screenshots taken from a video by Aaron Huggard on Youtube)

See video: 27ZX at www.everythingscience.co.za

In the experiment, the $Cu^{2+}$ ions from the **blue copper(II) sulfate** solution were reduced (gained electrons) to copper metal, which was then deposited as a layer on the solid zinc. The zinc atoms were oxidised (lost electrons) to form $Zn^{2+}$ ions in the solution. $Zn^{2+}(aq)$ is colourless, therefore the blue solution lost colour. As discussed in Grade 11, the half-reactions are as follows:

$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$ (reduction half-reaction)

$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$ (oxidation half-reaction)

The overall redox reaction is: $Cu^{2+}(aq) + Zn(s) \rightarrow Cu(s) + Zn^{2+}(aq)$

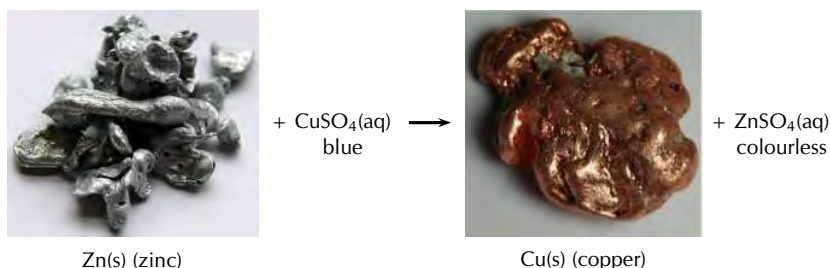



Figure 13.4: Solid zinc loses two electrons to form zinc ions ($Zn^{2+}$) in an aqueous solution of copper(II) sulfate. The copper ions ($Cu^{2+}$) gain two electrons and deposit as solid copper. (Photos by benjah-bmm27 and Jurii on wikipedia)

Remember that there was an increase in the temperature of the reaction when you carried out this experiment (it was exothermic). An exothermic reaction **releases energy**. This raises a few questions:

- Is it possible that this heat energy could be converted into electrical energy?
- Can we use a chemical reaction with an exchange of electrons, to produce electricity?
- If we supplied an electrical current could we *cause* some type of chemical reaction to take place?

The answers to these questions are the focus of this chapter:

- The energy of a chemical reaction can be converted to electrical potential energy, which forms an electric current.
- The transfer of electrons in a chemical reaction can cause electrical current to flow.
- If you supply an electric current it can cause a chemical reaction to take place, by supplying the electrons (and potential energy) necessary for the reactions taking place within the cell.

These types of reactions are called **electrochemical reactions**. An *electrochemical reaction* is a reaction where:

- a chemical reaction creates an *electrical potential difference*, and therefore an electric current in the external conducting wires

  ***or***

- an electric current provides electrical potential energy and electrons, and therefore a *chemical reaction takes place*

**DEFINITION:** *Electrochemical reaction*

An electrochemical reaction involves a transfer of electrons. There is a conversion of chemical potential energy to electrical potential energy, **or** electrical potential energy to chemical potential energy.

**Electrochemistry** is the branch of chemistry that studies these electrochemical reactions. An **electrochemical cell** is a device in which electrochemical reactions take place.

**DEFINITION:** *Electrochemical cell*

A device where electrochemical reactions take place.

### Exercise 13 – 3: Electrochemical reactions

1. In each of the following equations, say which elements in the reactants are oxidised and which are reduced.
   a) $CuO(s) + H_2(g) \rightarrow Cu(s) + H_2O(g)$
   b) $2NO(g) + 2CO(g) \rightarrow N_2(g) + 2CO_2(g)$
   c) $Mg(s) + FeSO_4(aq) \rightarrow MgSO_4(aq) + Fe(s)$
   d) $Zn(s) + 2AgNO_3(aq) \rightarrow 2Ag(s) + Zn(NO_3)_2(aq)$
2. Which one of the substances listed below acts as the oxidising agent in the following reaction?
   $3SO_2(g) + Cr_2O_7^{2-}(aq) + 2H^+(aq) \rightarrow 3SO_4^{2-}(aq) + 2Cr^{3+}(aq) + H_2O(\ell)$
   a) $H^+$ b) $Cr^{3+}$ c) $SO_2$ d) $Cr_2O_7^{2-}$
3. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 27ZY 2. 27ZZ

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**TIP**
**Oxidation** is the **loss of electrons**.
**Reduction** is the **gain of electrons**.

There are two types of electrochemical cells we will be looking more closely in this chapter: **galvanic** and **electrolytic cells**. Before we go into detail on galvanic and electrolytic cells you'll need to know a few definitions:

**DEFINITION:** *Electrode*

An electrode is an electrical conductor that connects the electrochemical species from its solution to the external electrical circuit of the cell.

There are two types of electrodes in an electrochemical cell, the **anode** and the **cathode**.

Oxidation always occurs at the **anode** while reduction always occurs at the **cathode**. So when trying to determine which electrode you are looking at first determine whether oxidation or reduction is occurring there. An easy way to remember this is:

**An Ox**
**O**xidation is **L**oss at the **A**node

**Red Cat**
**Red**uction is gain at the **Cat**hode

| | |
|---|---|
| **O**xidation **is** **l**oss of electrons | **OIL** |
| **R**eduction **is** **g**ain of electrons | **RIG** |
| **O**xidation is **l**oss of electrons at the **a**node | **An Ox** |
| **Red**uction is gain of electrons at the **cat**hode | **Red Cat** |

Table 13.1: A summary of phrases to help you remember the oxidation and reduction rules.

The electrode is placed in an **electrolyte** solution within the cell. If the cell is made up of two compartments, those compartments will be connected by a **salt bridge**.

**DEFINITION:** *Electrolyte*

An electrolyte is a solution that contains free ions, and which therefore behaves as a conductor of charges (electrical conductor) in solution.

**TIP**
Remember that cells are not 2-D, although when asked to sketch a cell you should draw it as shown in Figure 13.5 or Figure 13.6.

**DEFINITION:** *Salt bridge*

A salt bridge is a material which contains electrolytic solution and acts as a connection between two half-cells (completes the circuit). It maintains electrical neutrality in and between the electrolytes in the half-cell compartments.

## Galvanic cells ESCR5

A **galvanic cell** (which is also sometimes referred to as a **voltaic** or **wet** cell) consists of two half-cells, which convert chemical potential energy into electrical potential energy.

**TIP**
The electrons released in the oxidation of X remain on the anode, $X^+$ moves into solution.

The $Y^+$ ions are being reduced at the cathode and forming solid Y.

**DEFINITION:** *Galvanic cell*

A galvanic cell is an electrochemical cell which converts chemical potential energy to electrical potential energy through a spontaneous chemical reaction.

In a galvanic cell there are two half-cells. Each half-cell contains an electrode in an electrolyte. The separation is necessary to prevent direct chemical contact of the oxidation and reduction reactions, creating a potential difference. The electrons released in the oxidation reaction travel through an external circuit (and do work) before being used by the reduction reaction.

Figure 13.5: A sketch of a galvanic cell.

**In a galvanic cell** (for example the cell shown in Figure 13.5):

- The metal at the anode is **X**. **Ox**idation is loss of electrons at the **An**ode.
  - The **anode half-reaction** is $X(s) \rightarrow X^+(aq) + e^-$
  - This half-reaction occurs in the half-cell containing the X(s) anode and the $X^+$(aq) electrolyte solution.
  - The electrons released in the **oxidation** of the metal remain on the **anode**, while the metal cations formed move into solution.

  The metal at the cathode is Y. **Red**uction is gain of electrons at the **Cat**hode.
- 
  - The **cathode half-reaction** is $Y^+(aq) + e^- \rightarrow Y(s)$
  - This half-reaction occurs in the half-cell containing the Y(s) cathode and the $Y^+$(aq) electrolyte solution.
  - At the **cathode** metal ions in the solution are being **reduced** (accepting electrons) and deposited on the electrode.
- There are **more electrons** at the anode than at the cathode.
- Electrons will flow from areas of high concentration to areas of low concentration, therefore the electrons move **from the anode**, through the external circuit, **to the cathode**
- Conventional current is measured as a flow of positive charge and so is in the opposite direction (from the cathode to the anode)

- The overall reaction is: **X**(**s**) + **Y**$^{+}$(**aq**) → **X**$^{+}$(**aq**) + **Y**(**s**).
- To represent this reaction using **standard cell notation** we write the following:
  **X(s)|X$^{+}$(aq)||Y$^{+}$(aq)|Y(s)**
  By convention:
  - The **anode** is always written on the **left**.
  - The **cathode** is always written on the **right**.
  - The anode and cathode half-cells are divided by || representing the salt bridge.
  - The different phases within each half-cell (solid (s) and aqueous (aq) here) are separated by |.
- The electrodes in each half-cell are connected through a wire in the external circuit. There is also a salt bridge between the individual half-cells.

**FACT**
A spontaneous reaction is one that will occur without the need for external energy. Refer to the subsection on spontaneity for more information.

A galvanic cell uses the reactions that take place at at the two electrodes to produce electrical energy, i.e. the reaction occurs without the need to add energy.

The zinc-copper reaction you performed in Grade 11 can be modified to make a galvanic cell. Bars of zinc and copper are used as **electrodes**, with zinc(II) sulfate and copper(II) sulfate solutions as the **electrolytes**.

### Experiment: A galvanic cell

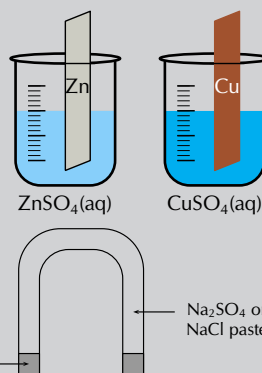
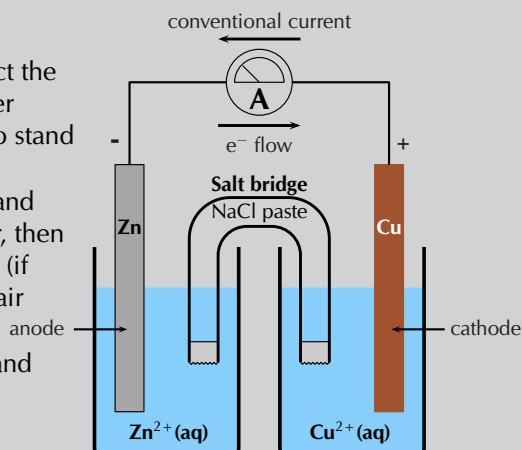
**Aim:**
To investigate the reactions that take place in a galvanic cell.

**Apparatus:**

- Zinc plate, copper plate, zinc(II) sulfate ($ZnSO_4$) solution (1 mol.dm$^{-3}$), copper(II) sulfate ($CuSO_4$) solution (1 mol.dm$^{-3}$), NaCl paste
- Measuring balance, two 250 ml beakers, U-tube, cotton wool, zero-centered ammeter, connecting wire.
- Cleaning ethanol, ether (if available)

**Method:**

1. Weigh the copper and zinc plates and record their mass.
2. Pour 200 ml of the zinc sulfate solution into a beaker and place the zinc plate in the beaker.
3. Pour 200 ml of the copper(II) sulfate solution into the second beaker and place the copper plate in the beaker.
4. Fill the U-tube with the NaCl paste and seal the ends of the tubes with the cotton wool (making a salt-bridge). The cotton will help stop the paste from dissolving in the electrolyte.

5. Connect the zinc and copper plates to the zero-centered ammeter and observe the ammeter.
6. Place the U-tube so that one end is in the copper(II) sulfate solution and the other end is in the zinc sulfate solution. Observe the ammeter.

7. Take the ammeter away and connect the copper and zinc plates to each other directly using copper wire. Leave to stand for about one day.
8. After a day, remove the two plates and rinse them: first with distilled water, then with alcohol, and finally with ether (if available). Dry the plates using a hair dryer.
9. Weigh the zinc and copper plates and record their mass.

**Note:**

A voltmeter can also be used in place of the zero-centered ammeter. A zero-centered voltmeter will measure the potential difference across the cell (not the flow of electrons), while an ammeter will measure the current.

**Discussion:**

- Did the ammeter record a reading before the salt-bridge was placed in the solutions?
- Did the ammeter record a reading after the salt-bridge was placed in the solutions? If yes, in what direction does the current flow?
- Fill in the table below:

| Plate | Initial mass | Final mass |
|---|---|---|
| Zinc | | |
| Copper | | |

- How did the mass of the zinc and copper plates change?
- Based on what you know of oxidation and reduction, why did those mass changes take place?
- Which electrode is the anode and which is the cathode?

**Results:**

During the experiment, you should have noticed the following:

- When the salt bridge was absent, there was no reading on the ammeter.
- When the salt bridge was connected, a reading was recorded on the ammeter.
- The direction of electron flow is from the zinc plate towards the copper plate, meaning that conventional current flow is from the copper plate towards the zinc plate.
- After the plates had been connected directly to each other and left for a day, there was a change in their mass. The mass of the zinc plate decreased, while the mass of the copper plate increased.
- **O**xidation **i**s **l**oss of electrons, **R**eduction **i**s **G**ain of electrons.

  The zinc electrode lost mass. This implies that solid Zn metal atoms become ions and move into the electrolyte solution: $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$. Oxidation occurs at the zinc electrode.

  The copper electrode gained mass. This implies that the Cu metal ions in the electrolyte solution become metal atoms and deposit on the electrode: $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$. Reduction occurs at the copper electrode.

- **Ox**idation is loss of electrons at the **an**ode. Oxidation occurs at the zinc electrode, therefore the zinc plate is the anode.

  **Red**uction is gain of electrons at the **cat**hode. Reduction occurs at the copper electrode, therefore the copper plate is the cathode.
- When $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$ the electrons are deposited on the anode, which becomes negatively charged.

  When $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$ the electrons are taken from the cathode, which becomes positively charged.

**Conclusions:**

When a zinc(II) sulfate solution containing a zinc plate is connected by a salt bridge to a copper(II) sulfate solution containing a copper plate, reactions occur in both solutions. The decrease in mass of the zinc plate suggests that the zinc metal electrode has been oxidised to form $Zn^{2+}$ ions in solution. The increase in mass of the copper plate suggests that reduction of $Cu^{2+}$ ions has occurred here to produce more copper metal.

**FACT**

It was the Italian physician and anatomist Luigi Galvani who marked the birth of electrochemistry by making a link between chemical reactions and electricity. In 1780, Galvani discovered that when two different metals (copper and zinc for example) were connected to each other and then both touched to different parts of a nerve of a frog leg at the same time, they made the leg contract. He called this 'animal electricity'.

The important thing to notice in this experiment is that:

- the chemical reactions that take place at the two electrodes cause an electric current to flow through the external circuit
- the overall reaction must be a spontaneous redox reaction
- **chemical energy** is converted to **electrical energy**
- the zinc-copper cell is one example of a **galvanic cell**

In the zinc-copper cell, the copper and zinc plates are the **electrodes**. The salt bridge plays a very important role in a galvanic cell:

- An electrolyte solution consists of metal cations and spectator anions.

  NaCl(aq) is $Na^+(aq)$ and $Cl^-(aq)$ in the paste.
- There is a build up of positive charge in the **anode half-cell compartment** as solid metal is **oxidised** and the positive ions move into solution. So there are more **postive metal ions** in the electrolyte than negative ions.

  **$Zn(s) \rightarrow Zn^{2+}(aq)$**, while the number of $SO_4^{2-}$ ions remains the same.
- To balance the charge, negative ions from the salt bridge move into the anode half-cell compartment.

  $Cl^-$ ions move from the salt bridge to the anode half-cell compartment.
- There is a decrease in positive charge in the **cathode half-cell compartment** as metal ions are **reduced** and form solid metal. So there are more **negative ions** in the electrolyte than positive metal ions.

  **$Cu^{2+}(aq) \rightarrow Cu(s)$**, while the number of $SO_4^{2-}$ ions remains the same.
- To balance the charge, positive ions from the salt bridge move into the cathode half-cell compartment.

  $Na^+$ ions move from the salt bridge to the cathode half-cell compartment.

The salt bridge acts as a transfer medium that allows ions to flow through without allowing the different solutions to mix and react directly. It allows a balancing of the charges in the electrolyte solutions, and allows the reactions in the cell to continue.

Without the salt bridge, the flow of electrons in the outer circuit stops completely. This is because the salt bridge is needed to complete the circuit.

**FACT**
Sometimes galvanic cells are just called electrochemical cells. While they are electrochemical cells, electrolytic cells are also electrochemical cells. Electrolytic and galvanic cells are not the same however.

## Electrolytic cells ESCR6

In an **electrolytic cell** electrical potential energy is converted to chemical potential energy. An electrolytic cell uses an electric current to force a particular chemical reaction to occur, which would otherwise not take place.

**DEFINITION:** *Electrolytic cell*

An electrolytic cell is an electrochemical cell that converts electrical potential energy to chemical potential energy by using electricity to drive a non-spontaneous chemical reaction.

An electrolytic cell is activated by applying an electrical potential across the electrodes to force an internal chemical reaction between the electrodes and the ions that are in the electrolyte solution. This process is called **electrolysis**.

**DEFINITION:** *Electrolysis*

Electrolysis is a method of driving chemical reactions by passing an electric current through an electrolyte.

**In an electrolytic cell** (for example the cell shown in Figure 13.6):

- The electrolyte solution consists of the metal cations and spectator anions.
- The oxidation and reduction reactions occur in the same container but are non-spontaneous.They require the electrodes to be connected to an external power source to proceed.
- The electrodes in an electrolytic cell can be the same metal or different metals. The prinicple is the same. Let there be only one metal, and let that metal be Z.

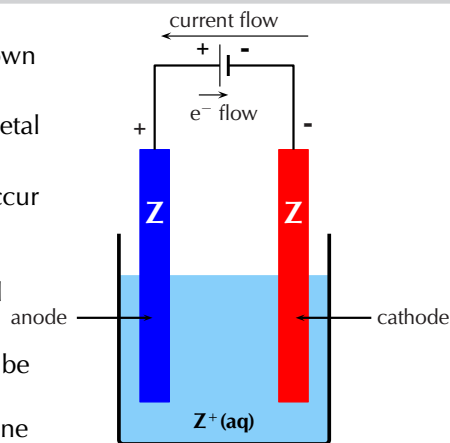



Figure 13.6: A sketch of an electrolytic cell.

- An electrode is connected to the **positive terminal** of the battery.
  - To balance the charge at the **positive electrode** metal atoms are **oxidised** to form metal ions. The ions move into solution, leaving their electrons on the electrode.
  - The following reaction takes place: **$Z(s) \rightarrow Z^{+}(aq) + e^{-}$**
  - **Ox**idation is loss at the **an**ode, therefore this electrode is the **anode**.
- An electrode is connected to the **negative terminal** of the battery.
  - When positive ions come in contact with the **negative electrode** the ions gain electrons and are **reduced**.
  - The following reaction takes place: **$Z^{+}(aq) + e^{-} \rightarrow Z(s)$**
  - **Red**uction is gain at the **cat**hode, therefore this electrode is the **cathode**.
- This means that the overall reaction is: $Z(s) + Z^{+}(aq) \rightarrow Z^{+}(aq) + Z(s)$. While this might seem trivial this is an important technique to purify metals (see Section 13.7).

**Experiment: The movement of coloured ions under the effect of electrical charge**

**Aim:**

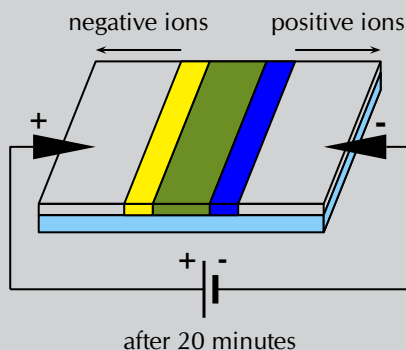
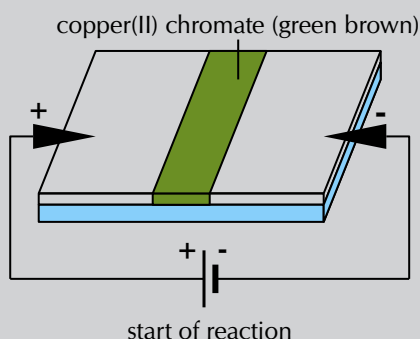
To demonstrate how ions migrate in solution towards oppositely charged electrodes.

**Apparatus:**

- Filter paper, glass slide, a 9V battery, two crocodile clips connected to wires, tape
- Ammonia ($NH_3$(aq)) and ammonium chloride ($NH_4Cl$) buffer solution, copper(II) chromate solution

**Method:**

1. Connect the wire from one crocodile clip to one end of the battery and secure with tape. Repeat with the other crocodile clip wire and the other end of the battery.
2. Soak a piece of filter paper in the ammonia and ammonium chloride buffer solution and place it on the glass slide.
3. Connect the filter paper to the battery using one of the crocodile clips, keep the other one nearby.
4. Place a line of copper(II) chromate solution at the centre of the filter paper. The colour of this solution is initially green-brown.
5. Attach the other crocodile clip opposite the first one (as shown in the diagram) and leave the experiment to run for about 20 minutes.

start of reaction

after 20 minutes

**Results:**

- After 20 minutes you should see that the central coloured band disappears and is replaced by two bands, one yellow and the other blue, which seem to have separated out from the first band of copper(II) chromate.
- The cell that is used to supply an electric current sets up a potential difference across the circuit, so that one of the electrodes is positive and the other is negative.
- The chromate ($CrO_4^{2-}$) ions in the copper(II) chromate solution are attracted to the positive electrode, this creates a yellow band. The $Cu^{2+}$ ions are attracted to the negative electrode, this creates a blue band.

**Conclusion:**

The movement of ions occurs because the electric current in the external circuit provides a potential difference between the two electrodes.

## Experiment: An electrolytic cell

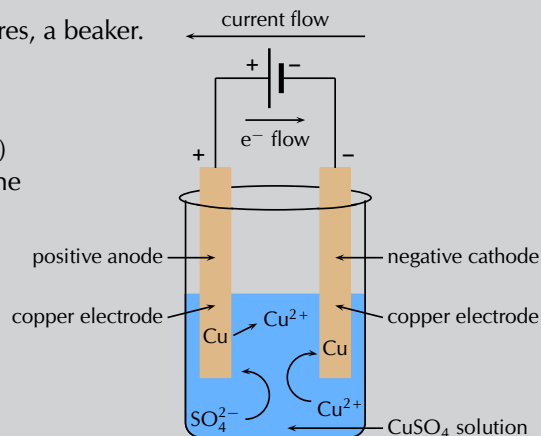
**Aim:**

To investigate the reactions that take place in an electrolytic cell.

**Apparatus:**

- Two copper plates (of equal size and mass), copper(II) sulfate ($CuSO_4$) solution (1 $mol.dm^{-3}$)
- A 9 V battery, two connecting wires, a beaker.

**Method:**

1. Half fill the beaker with copper(II) sulfate solution. What colour is the solution?
2. Weigh each copper electrode carefully and record the weight.
3. Place the two copper electrodes (of known mass) in the solution and make sure they are not touching each other.
4. Connect the electrodes to the battery as shown below and leave the experiment for a day. What colour is the solution after a day?

**Discussion:**

- What colour was the copper(II) sulfate solution before the experiment?
- What colour was the copper(II) sulfate solution after the experiment?
- Examine the two electrodes, what do you observe?
- What is the charge on each electrode?
- Which electrode is the anode and which is the cathode?

**Observations:**

- The initial blue colour of the solution remains unchanged throughout the experiment.
- It appears that copper has been *deposited* on one of the electrodes (it increased in mass) but *dissolved* from the other (it decreased in mass).
- The electrode connected to the negative terminal of the battery will have a negative charge. The electrode connected to the positive terminal of the battery will have a positive charge.
- When positively charged $Cu^{2+}$ ions encounter the negatively charged electrode they gain electrons and are reduced to form copper metal. This metal is deposited on the electrode. The half-reaction that takes place is as follows:

  $Cu^{2+}(aq) + 2e^{-} \rightarrow Cu(s)$ **(reduction half-reaction)**

  **Red**uction occurs at the **cat**hode. Therefore, the electrode which increased in mass is the cathode.
- At the positive electrode, copper metal is oxidised to form $Cu^{2+}$ ions, leaving electrons on the electrode. The half-reaction that takes place is as follows:

  $Cu(s) \rightarrow Cu^{2+}(aq) + 2e^{-}$ **(oxidation half-reaction)**

  **Ox**idation occurs at the **an**ode. Therefore, the electrode which decreased in mass is the anode.
- The amount of copper that is *deposited* at one electrode is approximately the same as the amount of copper that is *dissolved* from the other. The number of

$Cu^{2+}$ ions in the solution therefore remains almost the same, and the blue colour of the solution is unchanged.

**Conclusion:**
In this demonstration, the container held aqueous $CuSO_4$ ($Cu^{2+}$(aq) and $SO_4^{2-}$(aq)). The copper atoms of the electrode connected to the positive terminal (the anode) were oxidised and formed $Cu^{2+}$(aq) ions, causing a decrease in mass. The copper atoms of the electrode connected to the negative terminal (the cathode) were reduced to form solid copper, causing an increase in mass. This process is called *electrolysis*, and is very useful in the purification of metals.

Note that the cathode is negative and the anode is positive. Reduction still occurs at the cathode (Red Cat), and oxidation still occurs at the anode (An Ox).

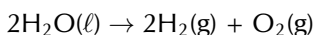
**TIP**

**FACT**

August Wilhelm von Hofmann was a German chemist who invented the Hofmann cell, which uses a current to form $H_2$(g) and $O_2$(g) from water through electrolysis.

### The electrolysis of water

Water can undergo electrolysis to form hydrogen gas and oxygen gas according to the following reaction:

$$2H_2O(\ell) \rightarrow 2H_2(g) + O_2(g)$$

This reaction is very important because hydrogen gas has the potential to be used as an energy source. The electrolytic cell for this reaction consists of two electrodes, submerged in an electrolyte and connected to a source of electric current (Figure 13.7).

The **oxidation half-reaction** is as follows:

$$2H_2O(\ell) \rightarrow O_2(g) + 4H^+(aq) + 4e^-$$

The **reduction half-reaction** is as follows:

$$2H^+(aq) + 2e^- \rightarrow H_2(g)$$

$H_2O + H_2SO_4$
$O_2$(g)
$H_2$(g)
graphite or platinum anode
graphite or platinum cathode
stopper
stopper
power supply

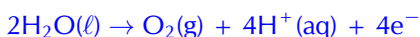
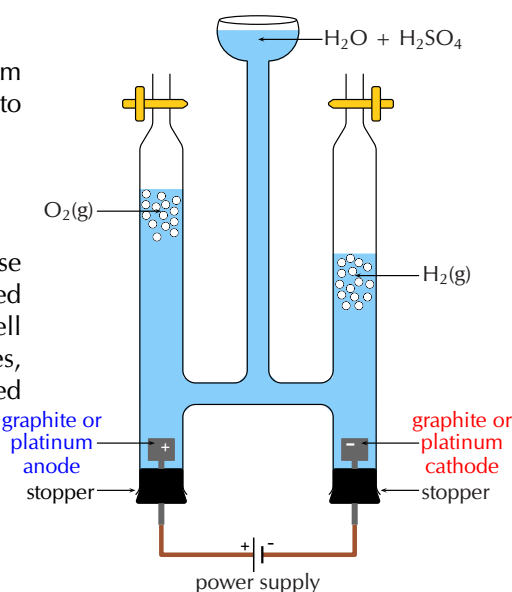



Figure 13.7: Hofmann apparatus for the electrolysis of water.

**Informal experiment: The electrolysis of sodium iodide and water**

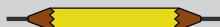
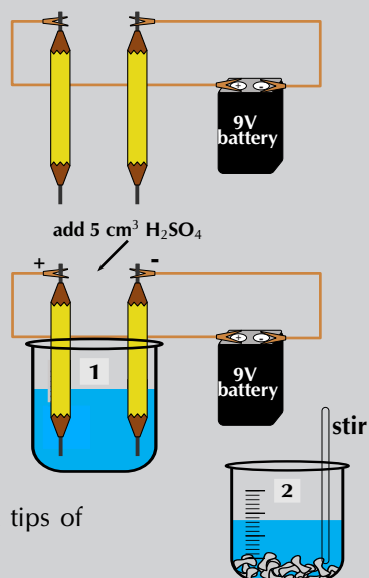
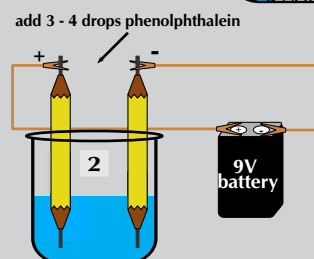
**Aim:**
To study the electrolysis of water and sodium iodide.

**Apparatus:**

- 4 pencils, copper wire attached to crocodile clips, 9 V battery, 2 beakers, pencil sharpener, spatula, glass rod
- distilled water, sodium iodide (NaI), phenolphthalein, 1 mol.dm$^{-3}$ sulfuric acid ($H_2SO_4$) solution

**Method:**

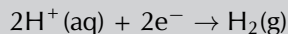
1. Label one beaker **1** and half fill it with distilled $H_2O$.

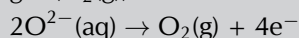
2. Sharpen both ends of two of the pencils. Strip away some of the wood to expose more of the graphite. (Graphite rods can be used instead of pencils if they are available).

3. Attach one end of the crocodile clips to the pencils and the other end to the battery.
4. Place the pencils in the beaker, making sure they are not touching each other. Observe what happens.
5. Pour approximately 5 $cm^3$ of the $H_2SO_4$ solution into the beaker. Observe what happens.
6. Label a second beaker **2** and add 5 spatula tips of NaI to the beaker.

7. Half fill beaker 2 with distilled $H_2O$ and stir with the glass rod until all the sodium iodide has dissolved.
8. Repeat steps 2 - 4 with the second set of pencils.
9. After a few minutes add 3 - 4 drops of the phenolphthalein to the beaker. Observe what happens.

**Questions:**

- In beaker **1**:
  1. What happened when the pencils were first put in the water?
  2. What happened when the sulfuric acid was added to the beaker?
  3. Why is the sulfuric acid necessary in this reaction?
  4. What is happening at the negative electrode (the pencil attached to the negative terminal of the battery)?
  5. What is happening at the positive electrode (the pencil attached to the positive terminal of the battery)?
  6. Which electrode is the anode and which is the cathode?
- In beaker **2**:
  1. What happened when the pencils were first put in the water?
  2. What is happening at the negative electrode?
  3. What is happening at the positive eletrode?
  4. Which electrode is the anode and which is the cathode?
  5. What happened when you added the phenolphthalein? Why did the change take place?

**Results:**

- In the electrolysis of water two $H^+$ ions each gain an electron (are reduced) and combine to form hydrogen gas ($H_2(g)$):

$2H^+(aq) + 2e^- \rightarrow H_2(g)$

Two $O^{2-}$ ions each lose two electrons (are oxidised) and combine to form oxygen gas ($O_2(g)$):

$2O^{2-}(aq) \rightarrow O_2(g) + 4e^-$

- When the positive $H^+$ ions encounter the negative electrode they are reduced. Reduction is a gain of electrons at the cathode, therefore the negative electrode is the cathode.
- When the negative $O^{2-}$ ions encounter the positive electrode they are oxidised. Oxidation is a loss of electrons at the anode, therefore the positive electrode is the anode.
- Remember that pure water does not conduct electricity. So, an electrolyte (such as sulfuric acid) is necessary for the reaction to take place.
- A salt dissolved in the water is also an electrolyte, so sulfuric acid is not necessary in the second beaker.
- The electrolysis of water occurs in beaker **2**, but there are other reactions taking place as well because of the presence of the $Na^+$ and $I^-$ ions.
- When the negative $I^-$ ions encounter the positive electrode they are oxidised:

  $2I^-(aq) \rightarrow I_2(s) + 2e^-$

  You should have observed solid iodine forming at the positive electrode.
- When the positive $Na^+$ ions encounter the negative electrode they are reduced:

  $Na^+(aq) + e^- \rightarrow Na(s)$

  Na(s) is very reactive with water:

  $2Na(s) + 2H_2O(\ell) \rightarrow 2NaOH(aq) + H_2(g)$.
- Remember that phenolphthalein turns pink in the presence of a base. So when the phenolphthalein is added, the water around the negative electrode should become pink due to the NaOH.

**Conclusion:**

The application of an electric current to water splits the water molecules and causes hydrogen and oxygen gas to form. This can only happen in the presence of an electrolyte (for example sulfuric acid). Sodium iodide dissolved in the water is also an electrolyte and enables the electrolysis of water. However, the cation and anion of the salt will also undergo a reaction. NaOH will form at the cathode, while solid iodine will form at the anode.

**Exercise 13 – 4: Galvanic and electrolytic cells**

1. An electrolytic cell consists of two electrodes in a silver chloride (AgCl) solution, connected to a source of current. A current is passed through the solution and $Ag^+$ ions are reduced to a silver metal deposit on one of the electrodes.
   a) What is the name of this process?
   b) Does reduction occur at the electrode where the deposit formed?
   c) Give the equation for the reduction half-reaction.
   d) Give the equation for the oxidation half-reaction.
2. A galvanic cell consists of two half-cells: a copper anode in a copper nitrate ($Cu(NO_3)_2(aq)$) solution, and a silver cathode in a silver nitrate ($AgNO_3(aq)$) solution.
   a) Give equations for the half-reactions that take place at the anode and cathode.

b) Write the overall reaction for this cell.
c) Give standard cell notation for this cell.
d) Draw a simple diagram of the galvanic cell.
On your diagram, show the direction in which current flows.

3. Electrolysis takes place in a solution of molten lead bromide ($PbBr_2$) to produce lead atoms.
   a) Give equations for the half-reactions that take place at the anode and cathode.
   b) Draw a simple diagram of the electrolytic cell.
   On your diagram, show the direction in which current flows.

4. Fill in the table below to summarise the information on galvanic and electrolytic cells:

| | Galvanic cells | Electrolytic cells |
|---|---|---|
| spontaneity | | |
| type of energy | | |
| anode | | |
| cathode | | |
| cell set-up | | |

5. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

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## 13.4 Processes in electrochemical cells ESCR7

### Half-cells and half-reactions ESCR8

Galvanic cells are actually made up of two half-cells. One half-cell contains the anode and an electrolyte containing the same metal cations. The other half-cell contains the cathode and an electrolyte containing the same metal cations. These half-cells are connected by a salt-bridge and the electrodes are connected through an external circuit.

Earlier in this chapter we discussed a zinc-copper cell. This was made up of a zinc **half-cell**, containing a zinc electrode and a zinc(II) sulphate ($ZnSO_4$) electrolyte solution, and a copper **half-cell**, containing a copper electrode and a copper(II) sulphate solution.

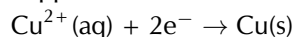
**DEFINITION:** *Half-cell*

A half-cell is a structure that consists of a conductive electrode surrounded by a conductive electrolyte.

In each half-cell a half-reaction takes place:

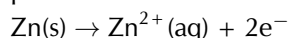
- **Copper plate**
  At the copper plate, there was an *increase* in mass. This means that $Cu^{2+}$ ions

from the copper(II) sulfate solution were deposited onto the plate as atoms of copper metal. The half-reaction that takes place at the copper plate is:

$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$

As electrons are gained by the copper ions this is the **reduction half-reaction**.

- **Zinc plate**

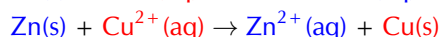
  At the zinc plate, there was a *decrease* in mass. This means that some of the solid zinc goes into solution as $Zn^{2+}$ ions. The electrons remain on the zinc plate, giving it a negative charge. The half-reaction that takes place at the zinc plate is:

  $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$

  As electrons are lost by the zinc atoms this is the **oxidation half-reaction**.

- **The overall reaction**

  You can then combine the two half-reactions from these two half-cells to get the overall reaction:

  $Zn(s) + Cu^{2+}(aq) + 2e^- \rightarrow Zn^{2+}(aq) + Cu(s) + 2e^-$ or, if we cancel the electrons:

  $Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s)$

It is possible to look at the half-reaction taking place in a half-cell and determine which electrode is the anode and which is the cathode.

- **Oxidation** is loss at the **anode**, therefore the oxidation half-reaction occurs in the half-cell containing the anode.
- **Reduction** is gain at the **cathode** so the reduction half-reaction occurs in the half-cell containing the cathode.

Remember that for an electrochemical cell the standard cell notation is:

**$Zn(s)|Zn^{2+}(aq)||Cu^{2+}(aq)|Cu(s)$**

$|$ = a phase boundary (solid/aqueous) $||$ = the salt bridge

**Worked example 4: Understanding galvanic cells**

***QUESTION***

For the following cell: $Zn(s)|Zn^{2+}(aq)||Ag^+(aq)|Ag(s)$

1. Give the anode and cathode half-reactions.
2. Write the overall equation for the chemical reaction.
3. Give the direction of the current in the external circuit.

***SOLUTION***

**Step 1: Identify the oxidation and reduction reactions**

By convention in standard cell notation, the anode is written on the left and the cathode is written on the right. So, in this cell:

Zinc is the anode (solid zinc is oxidised).

Silver is the cathode (silver ions are reduced).

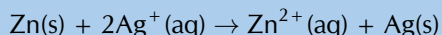
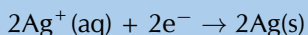
**Step 2: Write the two half-reactions**

Oxidation is loss of electrons at the anode: $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$

Reduction is gain of electrons at the cathode: $Ag^+(aq) + e^- \rightarrow Ag(s)$

**Step 3: Combine the half-reactions to get the overall equation**

Balance the charge by multiplying the reduction half-reaction by 2.

$2Ag^{+}(aq) + 2e^{-} \rightarrow 2Ag(s)$ $Zn(s) + 2Ag^{+}(aq) \rightarrow Zn^{2+}(aq) + Ag(s)$

**Step 4: Determine the direction of current flow**

The solid zinc is oxidised to form zinc ions. These electrons are left on the zinc electrode (anode) making it negative.

The silver ions take electrons and are reduced to form solid silver. This makes the silver electrode (cathode) positive.

Electron flow is from negative to positive, so from the anode to the cathode. Conventional current is in the opposite direction to electron flow. Therefore current will flow from the cathode (silver) to the anode (zinc).

**Exercise 13 – 5: Galvanic cells**

1. The following half-reactions take place in an electrochemical cell:

   $Fe(s) \rightarrow Fe^{3+}(aq) + 3e^{-}$ $Fe^{2+}(aq) + 2e^{-} \rightarrow Fe(s)$

   a) Which is the oxidation half-reaction?
   b) Which is the reduction half-reaction?
   c) Name the oxidising agent.
   d) Name the reducing agent.
   e) Use standard notation to represent this electrochemical cell.

2. For the following cell: $Mg(s)|Mg^{2+}(aq)||Mn^{2+}(aq)|Mn(s)$

   a) Give the cathode half-reaction.
   b) Give the anode half-reaction.
   c) Give the overall equation for the electrochemical cell.
   d) What metals could be used for the electrodes in this electrochemical cell?
   e) Suggest two electrolytes for this electrochemical cell.
   f) In which direction will the current flow?
   g) Draw a simple sketch of the complete cell.

3. For the following cell: $Sn(s)|Sn^{2+}(aq)||Ag^{+}(aq)|Ag(s)$

   a) Give the cathode half-reaction.
   b) Give the anode half-reaction.
   c) Give the overall equation for the electrochemical cell.
   d) Draw a simple sketch of the complete cell.

4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

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## Predictions in half-cells ESCR9

**Worked example 5: Reactions at the anode and cathode**

***QUESTION***

A cell contains a silver anode and a copper cathode. Give the half-cell reactions

occurring at the anode and cathode, as well as standard cell notation for this cell.

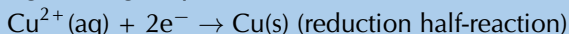
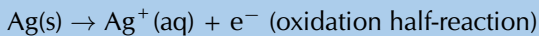
***SOLUTION***

**Step 1: What type of reaction occurs at the anode, and what type occurs at the cathode?**

Oxidation is loss of electrons at the anode. So the silver anode will be oxidised. Reduction is gain of electrons at the cathode. So the copper cathode will be reduced.

**Step 2: Write down the half-reactions as they would occur in the cell**

$Ag(s) \rightarrow Ag^{+}(aq) + e^{-}$ (oxidation half-reaction)

$Cu^{2+}(aq) + 2e^{-} \rightarrow Cu(s)$ (reduction half-reaction)

**Step 3: Give the standard cell notation for this reaction**

The anode is always written first (on the left): $Ag(s)|Ag^{+}(aq)$

The cathode is always written second (on the right): $Cu^{2+}(aq)|Cu(s)$

Therefore the standard cell notation is: $Ag(s)|Ag^{+}(aq)||Cu^{2+}(aq)|Cu(s)$

**Worked example 6: Determining overall reactions**

***QUESTION***

The following half-reactions take place in a cell:

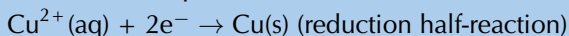
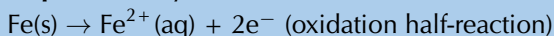
$Fe(s) \rightarrow Fe^{2+}(aq) + 2e^{-}$ $Cu^{2+}(aq) + 2e^{-} \rightarrow Cu(s)$

Determine the overall reaction that takes place as a balanced chemical equation and in standard cell notation.

***SOLUTION***

**Step 1: Identify the oxidation and reduction half-reactions**

$Fe(s) \rightarrow Fe^{2+}(aq) + 2e^{-}$ (oxidation half-reaction)

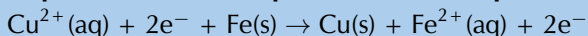
$Cu^{2+}(aq) + 2e^{-} \rightarrow Cu(s)$ (reduction half-reaction)

**Step 2: Which metal is the anode and which is the cathode?**

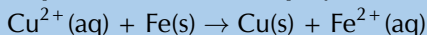
Oxidation is loss of electrons at the anode, therefore Fe is the anode. Reduction is gain of electrons at the cathode, therefore Cu is the cathode.

**Step 3: Compare the number of electrons in each equation**

There are 2 electrons in both equations, so the charges are balanced.

**Step 4: Combine the equations into one equation**

$Cu^{2+}(aq) + 2e^{-} + Fe(s) \rightarrow Cu(s) + Fe^{2+}(aq) + 2e^{-}$

**Step 5: Clean reaction up by combining appropriate ions and molecules**

$Cu^{2+}(aq) + Fe(s) \rightarrow Cu(s) + Fe^{2+}(aq)$

**Step 6: Give the standard cell notation for this reaction**

The anode is always written first (on the left): $Fe(s)|Fe^{2+}(aq)$

The cathode is always written second (on the right): $Cu^{2+}(aq)|Cu(s)$

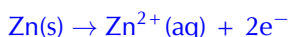
Therefore the standard cell notation is: $Fe(s)|Fe^{2+}(aq)||Cu^{2+}(aq)|Cu(s)$

## 13.5 The effects of current and potential on rate and equilibrium ESCRB

### Current and rate of reaction ESCRC

**A galvanic cell**

Let's think back to the Zn-Cu(s) electrochemical cell. This cell is made up of two half-cells and the reactions that take place at each of the electrodes are as follows:

$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^{-}$ $Cu^{2+}(aq) + 2e^{-} \rightarrow Cu(s)$

- At the zinc electrode, the zinc metal loses electrons and forms $Zn^{2+}$ ions. The electrons are concentrated on the zinc metal while the $Zn^{2+}$ ions are in solution.
- At the copper electrode, the copper ions gain electrons and forms solid copper.
- This means that there is an excess of electrons on the zinc anode, and a deficit of electrons on the copper cathode.
- Electrons will flow from an area of high concentration to an area of low concentration. Therefore the electrons on the zinc anode flow through the external circuit towards the more positive copper cathode.
- The larger the difference between the excess and the deficit of electrons, the faster the electrons will flow and the greater the current will be.
- The faster the electrons will flow, the greater the rate of the reaction must be.
- Therefore the larger the current, the faster the rate of the reaction.

**An electrolytic cell**

- Conversely, in an electrolytic cell a redox reaction takes place when a current is applied.
- This redox reaction is the decomposition of a chemical compound (electrolysis).
- The rate of this decomposition (into ions) is increased when the current applied is increased.

### Potential difference, equilibrium and concentration ESCRD

Again we can use the zinc-copper cell as an example.

When the chemical reaction between the zinc and the copper slows, the increase in product concentration, and the decrease in reactant concentration, slow too. This means that the electron transfer rate will decrease.

When the chemical reaction in the cell stops:

- The reaction is no longer converting chemical potential energy to electrical potential energy.
- The concentrations of the reactants and products have become constant and equilibrium has been reached.
- There is no excess or deficit of electrons on the electrodes, and the potential difference of the cell is 0.
- A potential difference of 0 means that the current is 0.

So the potential difference across a cell is related to the extent to which the cell reaction has reached equilibrium. When equilibrium is reached, the potential difference of the cell is zero and the cell is said to be 'flat'. There is no longer a potential difference between the two half-cells, and no more current will flow.

## 13.6 Standard electrode potentials ESCRF

### Standard conditions ESCRG

Standard electrode potentials are a measurement of equilibrium potentials. The position of this equilibrium can change if you change some of the conditions (e.g. concentration, temperature). It is therefore important that standard conditions be used:

- pressure = 101,3 kPa (1 atm)
- temperature = 298 K (25 °C)
- concentration = 1 $mol.dm^{-3}$

### The standard hydrogen electrode ESCRH

It is the **potential difference** (recorded as a voltage) between the two electrodes that causes electrons to flow from the **anode** to the **cathode** through the external circuit of a galvanic cell (remember, conventional current goes in the opposite direction).

It is possible to measure the potential of an electrode and electrolyte. It is not a simple process however, and the value obtained will depend on the concentration of the electrolyte solution, the temperature and the pressure.

A way to remove these inconsistencies is to compare all electrode potentials to a **standard reference electrode**. These comparisons are all done with the same concentrations, temperature and pressure. This means that these values can be used to calculate the potential difference between two electrodes. It also means that electrode potentials can be compared without the need to construct the specific cell being studied.

This reference electrode can be used to calculate the *relative* electrode potential for a substance. The reference electrode that is used is the **standard hydrogen electrode** (Figure 13.8).

**DEFINITION:** *Standard hydrogen electrode*

The standard hydrogen electrode is a redox electrode which forms the basis of the scale of oxidation-reduction potentials.

The standard hydrogen electrode consists of a platinum electrode in a solution containing $H^+$ ions. The solution (e.g. $H_2SO_4$) has a concentration of 1 $mol.dm^{-3}$. As the hydrogen gas bubbles over the platinum electrode, the reaction is as follows:

$$2H^+(aq) + 2e^- \rightleftharpoons H_2(g)$$

$H_2(g)$
(1 x atmospheric pressure)
Pt(s)
$[H^+]$
(1 $mol.dm^{-3}$)
25 °C

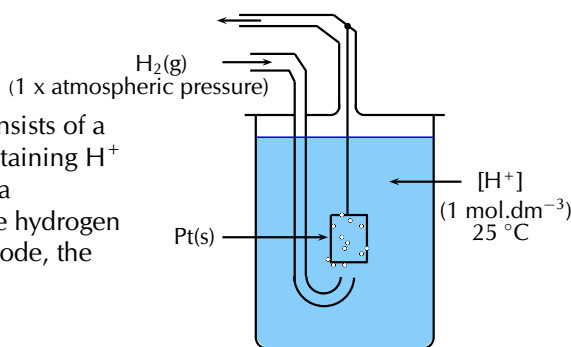
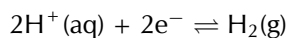



Figure 13.8: A simplified version of the standard hydrogen electrode.

**FACT**
The standard hydrogen electrode used now is actually the potential of a platinum electrode in a theoretical acidic solution.
The electrode potential of the hydrogen electrode at 25 °C is estimated to be 4,4 V. However, in order to use this as a reference electrode this value is set to **zero at all temperatures** so that it can be compared with other electrodes.

**FACT**
When determining standard electrode reduction potentials the standard hydrogen electrode is considered to be *on the left* (Pt(s)|$H_2$(g), $H^+$(aq)||). So a negative value means that the other element or compound has a greater tendency to oxidise, and a positive value means that the other element or compound has a greater tendency to be reduced.

**TIP**
By convention, we always write the reduction half-reaction when giving the standard electrode potential.

**TIP**
In the examples we used earlier, zinc's electrode reduction potential is −0,76 and copper's is +0,34. So, if an element or compound has a *negative* standard electrode reduction potential, it means it forms ions easily. The more negative the value, the easier it is for that element or compound to form ions (be oxidised, and be a reducing agent). If an element or compound has a *positive* standard electrode potential, it means it does not form ions as easily.

## Standard electrode potentials ESCRJ

In order to *use* the hydrogen electrode, it needs to be attached to the electrode system that you are investigating. For example, if you are trying to determine the electrode potential of copper, you will need to connect the copper half-cell to the hydrogen electrode; if you are trying to determine the electrode potential of zinc, you will need to connect the zinc half-cell to the hydrogen electrode and so on. Let's look at the examples of zinc and copper in more detail.

### Zinc

Zinc has a greater tendency than hydrogen to form ions (to be oxidised), so if the standard hydrogen electrode is connected to the zinc half-cell, the **zinc** will be relatively **more negative** because the electrons that are released when zinc is oxidised will accumulate on the metal.

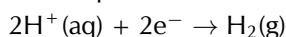
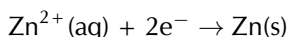
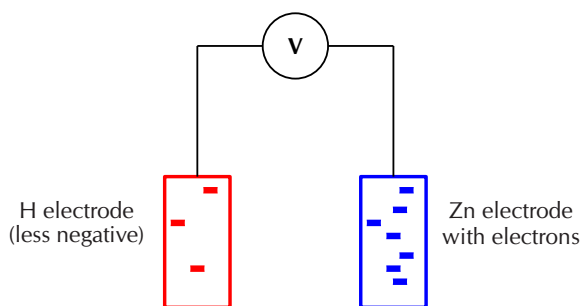
$Zn^{2+}(aq) + 2e^{-} \rightarrow Zn(s)$
$2H^{+}(aq) + 2e^{-} \rightarrow H_2(g)$

The solid zinc is more likely to form zinc ions than the hydrogen gas is to form ions. A simplified representation of the cell is shown in Figure 13.9.



Figure 13.9: When zinc is connected to the standard hydrogen electrode, relatively few electrons build up on the platinum (hydrogen) electrode. There are lots of electrons on the zinc electrode.

The voltmeter measures the potential difference between the charge on these electrodes. In this case, the voltmeter would read −0,76 V as the Zn electrode has a relatively higher number of electrons.

### Copper

Copper has a lower tendency than hydrogen to form ions, so if the standard hydrogen electrode is connected to the copper half-cell, the **copper** will be relatively **less negative**.

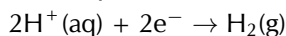
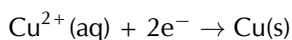
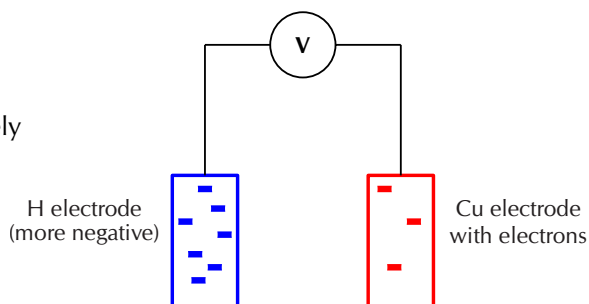
$Cu^{2+}(aq) + 2e^{-} \rightarrow Cu(s)$
$2H^{+}(aq) + 2e^{-} \rightarrow H_2(g)$

The copper ions are more likely to form solid copper than the hydrogen ions are to form hydrogen gas. A simplified representation of the cell is shown in Figure 13.10.



Figure 13.10: When copper is connected to the standard hydrogen electrode, relatively few electrons build up on the copper electrode. There are lots of electrons on the hydrogen electrode.

The voltmeter measures the potential difference between the charge on these electrodes. In this case, the voltmeter would read +0,34 V as the Cu electrode has a relatively lower number of electrons.

The voltages recorded when zinc and copper were connected to a standard hydrogen electrode are in fact the **standard electrode potentials** for these two metals. It is important to remember that these are not *absolute* values, but are potentials that have been measured *relative* to the potential of hydrogen if the standard hydrogen electrode is taken to be zero.

Luckily for us, we do not have to determine the standard electrode potential for every metal. This has been done already and the results are recorded in a table of standard electrode potentials. Table 13.2 is presented as the standard electrode reduction potentials.

| Half-Reaction | E° V |
|---|---|
| $Li^+ + e^- \rightleftharpoons Li$ | −3,04 |
| $K^+ + e^- \rightleftharpoons K$ | −2,92 |
| $Ba^{2+} + 2e^- \rightleftharpoons Ba$ | −2,90 |
| $Ca^{2+} + 2e^- \rightleftharpoons Ca$ | −2,87 |
| $Na^+ + e^- \rightleftharpoons Na$ | −2,71 |
| $Mg^{2+} + 2e^- \rightleftharpoons Mg$ | −2,37 |
| $Al^{3+} + 3e^- \rightleftharpoons Al$ | −1,66 |
| $Mn^{2+} + 2e^- \rightleftharpoons Mn$ | −1,18 |
| $2H_2O + 2e^- \rightleftharpoons H_2(g) + 2OH^-$ | −0,83 |
| $Zn^{2+} + 2e^- \rightleftharpoons Zn$ | −0,76 |
| $Cr^{2+} + 2e^- \rightleftharpoons Cr$ | −0,74 |
| $Fe^{2+} + 2e^- \rightleftharpoons Fe$ | −0,44 |
| $Cr^{3+} + 3e^- \rightleftharpoons Cr$ | −0,41 |
| $Cd^{2+} + 2e^- \rightleftharpoons Cd$ | −0,40 |
| $Co^{2+} + 2e^- \rightleftharpoons Co$ | −0,28 |
| $Ni^{2+} + 2e^- \rightleftharpoons Ni$ | −0,25 |
| $Sn^{2+} + 2e^- \rightleftharpoons Sn$ | −0,14 |
| $Pb^{2+} + 2e^- \rightleftharpoons Pb$ | −0,13 |
| $Fe^{3+} + 3e^- \rightleftharpoons Fe$ | −0,04 |
| $2H^+ + 2e^- \rightleftharpoons H_2(g)$ | **0,00** |
| $S + 2H^+ + 2e^- \rightleftharpoons H_2S(g)$ | +0,14 |
| $Sn^{4+} + 2e^- \rightleftharpoons Sn^{2+}$ | +0,15 |
| $Cu^{2+} + e^- \rightleftharpoons Cu^+$ | +0,16 |
| $SO_4^{2-} + 4H^+ + 2e^- \rightleftharpoons SO_2(g) + 2H_2O$ | +0,17 |
| $Cu^{2+} + 2e^- \rightleftharpoons Cu$ | +0,34 |
| $2H_2O + O_2 + 4e^- \rightleftharpoons 4OH^-$ | +0,40 |
| $Cu^+ + e^- \rightleftharpoons Cu$ | +0,52 |
| $I_2 + 2e^- \rightleftharpoons 2I^-$ | +0,54 |
| $O_2(g) + 2H^+ + 2e^- \rightleftharpoons H_2O_2$ | +0,68 |
| $Fe^{3+} + e^- \rightleftharpoons Fe^{2+}$ | +0,77 |
| $NO_3^- + 2H^+ + e^- \rightleftharpoons NO_2(g) + H_2O$ | +0,78 |
| $Hg^{2+} + 2e^- \rightleftharpoons Hg(\ell)$ | +0,78 |
| $Ag^+ + e^- \rightleftharpoons Ag$ | +0,80 |
| $NO_3^- + 4H^+ + 3e^- \rightleftharpoons NO(g) + 2H_2O$ | +0,96 |
| $Br_2 + 2e^- \rightleftharpoons 2Br^-$ | +1,06 |
| $O_2(g) + 4H^+ + 4e^- \rightleftharpoons 2H_2O$ | +1,23 |
| $MnO_2 + 4H^+ + 2e^- \rightleftharpoons Mn^{2+} + 2H_2O$ | +1,28 |
| $Cr_2O_7^{2-} + 14H^+ + 6e^- \rightleftharpoons 2Cr^{3+} + 7H_2O$ | +1,33 |
| $Cl_2 + 2e^- \rightleftharpoons 2Cl^-$ | +1,36 |
| $Au^{3+} + 3e^- \rightleftharpoons Au$ | +1,50 |
| $MnO_4^- + 8H^+ + 5e^- \rightleftharpoons Mn^{2+} + 4H_2O$ | +1,52 |
| $Co^{3+} + e^- \rightleftharpoons Co^{2+}$ | +1,82 |
| $F_2 + 2e^- \rightleftharpoons 2F^-$ | +2,87 |

Table 13.2: Table of standard electrode (reduction) potentials.

A few examples from the table are shown in Table 13.3. These will be used to explain some of the trends in the table of electrode potentials.

| Half-Reaction | E° V |
|---|---|
| $Li^+ + e^- \rightleftharpoons Li$ | −3,04 |
| $Mg^{2+} + 2e^- \rightleftharpoons Mg$ | −2,37 |
| $Zn^{2+} + 2e^- \rightleftharpoons Zn$ | −0,76 |
| $Fe^{3+} + 3e^- \rightleftharpoons Fe$ | −0,4 |
| $Pb^{2+} + 2e^- \rightleftharpoons Pb$ | −0,13 |
| $2H^+ + 2e^- \rightleftharpoons H_2(g)$ | **0,00** |
| $Cu^{2+} + 2e^- \rightleftharpoons Cu$ | +0,34 |
| $Ag^+ + e^- \rightleftharpoons Ag$ | +0,80 |
| $Au^{3+} + 3e^- \rightleftharpoons Au$ | +1,50 |

Table 13.3: A few examples of standard electrode potentials.

- A **large negative value** (e.g. $Li^+ + e^- \rightleftharpoons Li$) means that the element or compound ionises easily, in other words, it releases electrons easily. This element or compound is **easily oxidised** and is therefore a good **reducing agent**.
- A **large positive value** (e.g. $Au^{3+} + e^- \rightleftharpoons Au$) means that the element or compound gains electrons easily. This element or compound is **easily reduced** and is therefore a good **oxidising agent**.
- The **reducing ability** (i.e. the ability to act as a reducing agent) of the elements or compounds in the table **decreases** as you move **down** in the table.
- The **oxidising ability** of elements or compounds **increases** as you move **down** in the table.

**Experiment: Ice cube tray redox experiment**

**Aim:**

To determine relative reactivity of the respective metals and to gain understanding of the workings of a simple electrochemical cell.

**Apparatus:**

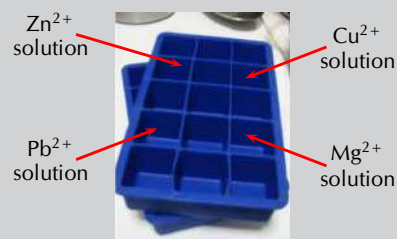
- Ice cube tray, voltmeter and connecting wires.
- Lead (Pb), magnesium (Mg), zinc (Zn), copper (Cu) strips.
- 1 $mol.dm^{-3}$ solutions of lead (e.g. $PbSO_4$), magnesium (e.g. $MgSO_4$), zinc (e.g. $ZnSO_4$) and copper (e.g. $CuSO_4$).
- String soaked in a sodium nitrate ($NaNO_3$) solution.

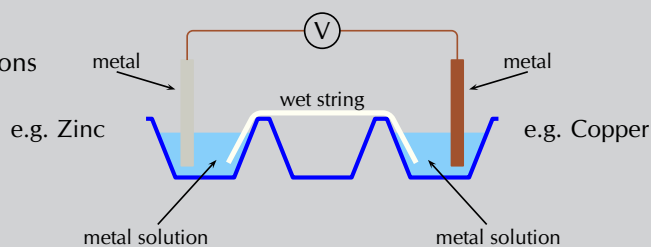
**Pre-knowlege:**

Electrons move from the anode to the cathode. Conventional current moves from the cathode to the anode - therefore the positive terminal of the voltmeter will be on the cathode and the negative terminal will be on the anode.

**Method:**

1. Place approximately 15 $cm^3$ of the Pb, Zn, Cu and Mg solutions into four different ice cube depressions. These should not be next to each other to avoid mixing of solutions.

2. Attach two different metals to the crocodile clips. Drape the wet string across the two solutions being used (so that each end of the string is in a solution). Then place the metal into its respective ion solution.
   i.e. zinc electrode **must** go into the $Zn^{2+}$ solution, copper electrode **must** go into the $Cu^{2+}$ solution.

Use the cell combinations in the following order:

Pb/Zn; Pb/Cu; Pb/Mg; Zn/Cu; Zn/Mg; Cu/Mg

3. Determine the combinations of metals that give a positive reading.
4. Draw up a table that shows:
   - the combination of the metals
   - which metal is the anode in that pair of metals
   - which metal is the cathode in that pair of metals

| Metal combination | Anode | Cathode |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

5. Use this table to rank the metals from the strongest **reducing agent** (rank from the strongest to the weakest).
6. For each combination - write down the reduction half-reaction and oxidation half-reaction and then the overall cell reaction.
7. Note all observations for each cell.

**Questions:**

1. Explain why the voltages appear to be lower/higher than expected.
2. What is the purpose of the string?

**Conclusions:**

Depending on the electrode potential of each metal, the same metal could be the anode in one reaction and the cathode in another reaction. This can be seen by the positive, or negative, reading on the voltmeter.

For example, lead is more likely to be reduced than zinc, therefore in that pair lead will be the cathode and zinc will be the anode. However, lead is more likely to be oxidised than copper, therefore in that pair copper will be the cathode and lead will be the anode.

**Exercise 13 – 6: Table of standard electrode potentials**

1. Give the standard electrode potential for each of the following metals:
   a) magnesium
   b) lead
   c) nickel
2. Refer to the electrode potentials in Table 13.2.
   a) Which of the metals is most likely to be oxidised?
   b) Which metal ion is most likely to be reduced?

**TIP**
In this worked example you are given two half-reactions. Both are presented as shown in the table of standard reduction potentials, but in reality only one metal is being reduced, the other is being oxidised. The question being asked is: Which metal is being oxidised and which is being reduced?

c) Which metal is the strongest reducing agent?
d) If the other electrode is magnesium, is reduction or oxidation more likely to take place in the copper half-reaction? Explain your answer.
e) If the other electrode is tin, is reduction or oxidation more likely to take place in the mercury half-reaction? Explain your answer.

3. Use the table of standard electrode potentials to put the following in order from the **strongest oxidising agent** to the **weakest oxidising agent**.
   - $Cu^{2+}$
   - $MnO_4^-$
   - $Br_2$
   - $Zn^{2+}$
4. Look at the following half-reactions:
   - $Ca^{2+}(aq) + 2e^- \rightarrow Ca(s)$
   - $Cl_2(g) + 2e^- \rightarrow 2Cl^-(aq)$
   - $Fe^{3+}(aq) + 3e^- \rightarrow Fe(s)$
   - $I_2(s) + 2e^- \rightarrow 2I^-(aq)$

   a) Which substance is the strongest oxidising agent?
   b) Which substance is the strongest reducing agent?
5. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1a. 2829 1b. 282B 1c. 282C 2. 282D 3. 282F 4. 282G

 www.everythingscience.co.za  m.everythingscience.co.za

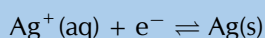
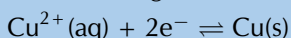
## Uses of the standard electrode potentials ESCRK

So now that you understand this useful table of reduction potentials, it is important that you can use these values to calculate the potential energy differences. The following worked examples will help you do this. In all of these cases it is important that you understand what the question is asking.

**Worked example 7: Using the table of standard electrode potentials**

***QUESTION***

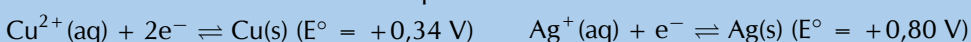
The following reactions take place in an electrochemical cell:

$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$ $Ag^+(aq) + e^- \rightleftharpoons Ag(s)$

Determine which reaction is the oxidation half-reaction and which is the reduction half-reaction in this cell.

***SOLUTION***

**Step 1: Determine the electrode potential for each metal**

From the table of standard electrode potentials:

$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$ ($E^\circ = +0,34$ V) $Ag^+(aq) + e^- \rightleftharpoons Ag(s)$ ($E^\circ = +0,80$ V)

**Step 2: Use the electrode potential values to determine which metal is oxidised and which is reduced**

Both values are positive, but silver has a larger, positive electrode potential than copper. Therefore silver is more easily reduced than copper, and copper is more easily oxidised than silver.

**Step 3: Write the reduction and oxidation half-reactions**

The E° values are taken from the table of standard **reduction** potentials. Therefore the reduction half-reaction is as seen in the table.

The reduction half-reaction: $Ag^{+}(aq) + e^{-} \rightarrow Ag(s)$ (reduction is a gain of electrons)
Oxidation is a loss of electrons, and so would be written in reverse.
The oxidation half-reaction: $Cu(s) \rightarrow Cu^{2+}(aq) + 2e^{-}$.

**TIP**
If magnesium is able to displace silver from a solution of silver nitrate, this means that magnesium metal will form magnesium ions and the silver ions will become silver metal. In other words, there will now be **silver** metal and a solution of **magnesium nitrate**. This will only happen if magnesium has a greater tendency than silver to form ions. In other words, what this worked example is asking is whether magnesium or silver will form ions more easily.

**TIP**
Remember that solid metal will not always be formed when an ion is reduced. For example $Sn^{4+} + 2e^{-} \rightarrow Sn^{2+}$.

### Worked example 8: Using the table of standard electrode potentials

***QUESTION***

Is magnesium able to displace silver from a solution of silver nitrate?

***SOLUTION***

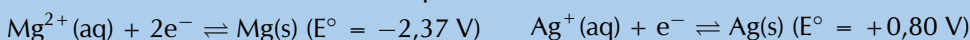
**Step 1: Find appropriate reactions on the table of standard electrode potentials**

The reaction involves magnesium and silver.

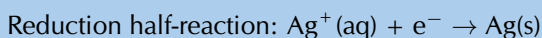
$Mg^{2+}(aq) + 2e^{-} \rightleftharpoons Mg(s)$ $\qquad$ $Ag^{+}(aq) + e^{-} \rightleftharpoons Ag(s)$

**Step 2: Determine the electrode potential for each metal**

From the table of standard electrode potentials:

$Mg^{2+}(aq) + 2e^{-} \rightleftharpoons Mg(s)$ ($E^{\circ} = -2,37$ V) $\qquad$ $Ag^{+}(aq) + e^{-} \rightleftharpoons Ag(s)$ ($E^{\circ} = +0,80$ V)

**Step 3: Which metal is more likely to be reduced, which is more likely to be oxidised?**

Silver has a positive $E^{\circ}$, while magnesium has a negative $E^{\circ}$. Therefore silver is more easily reduced than magnesium, and magnesium is more easily oxidised than silver. The following reactions would occur:

Reduction half-reaction: $Ag^{+}(aq) + e^{-} \rightarrow Ag(s)$
Oxidation half-reaction: $Mg(s) \rightarrow Mg^{2+}(aq) + 2e^{-}$

It can be concluded that magnesium **will** displace silver from a silver nitrate solution so that there will be silver metal and magnesium ions in the solution.

### Worked example 9: Determining overall reactions

***QUESTION***

For a zinc (Zn) and gold(III) oxide ($Au_2O_3$) cell in solution of KOH determine the:

- oxidation and reduction half-reactions
- overall balanced chemical equation
- standard cell notation for the cell

***SOLUTION***

**Step 1: Find appropriate reactions on the table of standard electrode potentials**

The reaction involves zinc and gold.

$Zn^{2+}(aq) + 2e^{-} \rightleftharpoons Zn(s)$ $\qquad$ $Au^{3+}(aq) + 3e^{-} \rightleftharpoons Au(s)$

**Step 2: Determine the electrode potential for each metal**

From the table of standard electrode potentials:

$Zn^{2+}(aq) + 2e^{-} \rightleftharpoons Zn(s)$ ($E^{\circ} = -0,76$ V) $\qquad$ $Au^{3+}(aq) + 3e^{-} \rightleftharpoons Au(s)$ ($E^{\circ} = +1,50$ V)

**Step 3: Which metal is more likely to be reduced, which is more likely to be oxidised?**

Zinc has a negative E°, while gold has a positive E°. Therefore gold is more easily reduced than zinc, and zinc is more easily oxidised than gold. The following reactions would occur:

Reduction half-reaction: $Au^{3+}(aq) + 3e^{-} \rightarrow Au(s)$

Oxidation half-reaction: $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^{-}$

**Step 4: Compare the number of electrons in each equation**

There are 3 electrons in the reduction half-reaction, and 2 electrons in the oxidation half-reaction.

**Oxidation:** $\times 3$: $3Zn(s) \rightarrow 3Zn^{2+}(aq) + \mathbf{6e}^{-}$

**Reduction:** $\times 2$: $2Au^{3+}(aq) + \mathbf{6e}^{-} \rightarrow 2Au(s)$

**Step 5: Combine the equations into one equation**

$2Au^{3+}(aq) + 6e^{-} + 3Zn(s) \rightarrow 2Au(s) + 3Zn^{2+}(aq) + 6e^{-}$

**Step 6: Add the spectator ions and remove the electrons from the equation**

$Au_2O_3(aq) + 3Zn(s) \rightarrow 2Au(s) + 3ZnO(aq)$

**Step 7: Which material is the anode and which is the cathode?**

Oxidation is loss of electrons at the anode, therefore Zn(s) is the anode.

Reduction is gain of electrons at the cathode, therefore $Au_2O_3$ is the cathode.

**Step 8: Give the standard cell notation for this reaction**

The anode is always written first (on the left): $Zn(s)|ZnO(aq)$

The cathode is always written second (on the right): $Au_2O_3(s), Au(s)$

Therefore the standard cell notation is: $Zn(s)|ZnO(aq)||Au_2O_3(s), Au(s)$

**Experiment: Displacement experiment**

**Aim:**

To demonstrate the effect of reacting a halogen with a halide.

**Apparatus:**

- Bleach (approximately 10 $cm^3$), bromine water, aqueous solutions of sodium chloride (NaCl), sodium bromide (NaBr) and sodium iodide (NaI), paraffin, concentrated HCl.
- 5 test tubes, 2 plastic droppers.

**Method:**

**WARNING!**

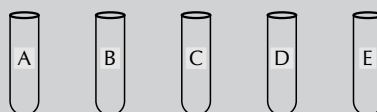
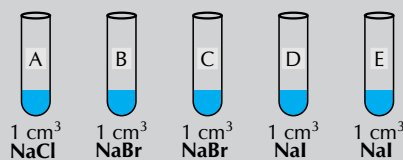
---

**Concentrated HCl can cause serious burns. We suggest using gloves and safety glasses whenever you work with an acid. Remember to add the acid to the water and to avoid sniffing the acid. Handle all chemicals with care.**

---

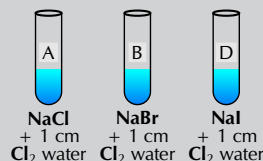
1. Label the test tubes A, B, C, D and E.

A

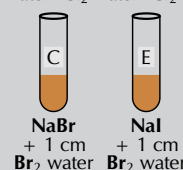
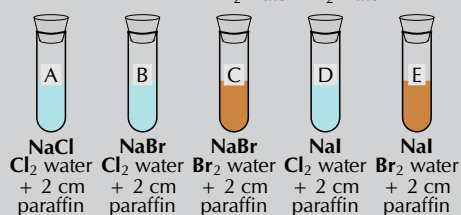
C

2. Place 1 $cm^3$ NaCl solution into test tube A.
3. Place 1 $cm^3$ NaBr solution into both test tubes B and C.
4. Place 1 $cm^3$ NaI solution into both test tubes D and E.

5. Activate 10 $cm^3$ of the bleach by adding 2 $cm^3$ of the concentrated HCl.

   Observe the liquid and note what happens on adding HCl, record your observations. *You have formed a solution of chlorine in water*.
6. Using a plastic dropper transfer approximately 1 cm height of the chlorine water into the test tubes labelled A, B and D.

   Note any changes to the test tube. Record all observations.

A: NaCl + 1 cm $Cl_2$ water
B: NaBr + 1 cm $Cl_2$ water
D: NaI + 1 cm $Cl_2$ water

7. Pour 1 $cm^3$ of bromine water into the test tubes labelled C and E.

   Note any changes to the test tube. Record all observations.

C: NaBr + 1 cm $Br_2$ water
E: NaI + 1 cm $Br_2$ water

8. Using a plastic dropper transfer approximately 2 cm height of the paraffin into each test tube. Use a cork or rubber stopper to close the test tube, hold it firmly in place with your thumb, and shake the mixture.

9. Use the redox table to write overall net ionic equations for the reactions in test tubes B, D and E.
10. Using your understanding of solubility rules (*like dissolves like*) explain why the layer of paraffin became coloured in test tubes B, D and E. Explain what caused the paraffin to become coloured in test tube C.
11. Why was there no reaction and no colour change in test tube A?

**Results:**

- In test tube A $Cl_2$ is present, but is not coloured and so no change in the colour of the paraffin is observed.
- In test tubes B and D the chlorine displaces the $Br^-$ and $I^-$ ions. $Br_2$ and $I_2$ are formed.

  $Br_2$ is a brown colour in paraffin, while $I_2$ is a purple colour in paraffin.
- In test tube C the $Br_2$ was already present and coloured the paraffin a brown colour.
- In test tube E the $Br_2$ displaced the $I^-$ ions to form $I_2$ which would turn the paraffin a purple colour.

**Conclusion:**

Halogen molecules are non-polar. They will therefore dissolve in a non-polar solvent such as paraffin. The paraffin layer will become the colour of the halogen present in the solution. Chlorine is the most likely of these three halogens to be reduced, followed by bromine, and then iodine. This can be seen on the standard electrode potential table as chlorine has the largest, positive electrode potential of the three halogens.

**FACT**
The EMF of a cell is a the same as the **voltage** across a disconnected cell (*electric circuit theory*). A voltmeter is effectively a high resistance ammeter, so a very small current will flow when a voltmeter reading is taken (although this is too small to be noticeable).

**TIP**
**Remember:**
Standard conditions are:
p = 101,3 kPa
C = 1 $mol.dm^{-3}$
T = 298 K.

--------------
In standard cell notation the **anode half-cell** is always written on the left and the **cathode half-cell** is always written on the right.

--------------
The reducing agent is being oxidised. Oxidation is a loss of electrons at the anode.

The oxidising agent is being reduced. Reduction is a gain of electrons at the cathode.

**Exercise 13 – 7: Using standard electrode potentials**

1. If silver was added to a solution of copper(II) sulfate, would it displace the copper from the copper(II) sulfate solution? Explain your answer.
2. If zinc is added to a solution of magnesium sulfate, will the zinc displace the magnesium from the solution? Give a detailed explanation for your answer.
3. If aluminium is added to a solution of cobalt sulfate, will the aluminium displace the cobalt from the solution? Give a detailed explanation for your answer.
4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 282H 2. 282J 3. 282K

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## EMF of a cell ESCRM

Using the example of the zinc and copper half-cells, we know that when these two half-cells are combined, zinc will be the oxidation half-reaction and copper will be the reduction half-reaction. A voltmeter connected to this cell will show that the zinc electrode is more negative than the copper electrode.

$Cu^{2+}(aq) + 2e^{-} \rightleftharpoons Cu(s)$ ($E^{\circ} = +0,34$ V) $Zn^{2+}(aq) + 2e^{-} \rightleftharpoons Zn(s)$ ($E^{\circ} = -0,76$ V)

The reading on the meter will show the potential difference between the two half-cells. This is known as the **EMF** of the cell. The higher the EMF, the greater amount of energy released per unit charge.

**DEFINITION:** *EMF of a cell*

The EMF of a cell is defined as the maximum potential difference between two electrodes or half-cells in a galvanic cell.

It is important to be able to calculate the EMF of an electrochemical cell. To calculate the EMF of a cell:

- take the E° of the atom that is being reduced
- subtract the E° of the atom that is being oxidised

The reason for defining a reference electrode becomes obvious now. Potential differences can be calculated from the electrode potentials (determined relative to the hydrogen half-cell) without having to construct the cells themselves each time.

You can use any one of the following equations:

- $E^{\circ}_{(cell)}$ = E°(reduction half-reaction) - E°(oxidation half-reaction)
- $E^{\circ}_{(cell)}$ = E°(oxidising agent) - E°(reducing agent)
- $E^{\circ}_{(cell)}$ = E°(cathode) - E°(anode)

So, for the Zn-Cu cell: $E^{\circ}_{(cell)} = 0,34 - (-0,76) = 0,34 + 0,76 = 1,10$ V

**DEFINITION:** *Standard EMF*

Standard EMF ($E^{\circ}_{cell}$) is the EMF of a galvanic cell operating under standard conditions. The symbol ° denotes standard conditions.

**Worked example 10: Calculating the EMF of a cell**

***QUESTION***

A cell contains a solid lead anode in a gold ion solution.

1. Represent the cell using standard notation.
2. Calculate the cell potential (EMF) of the electrochemical cell.

***SOLUTION***

**Step 1: Find appropriate reactions on the table of standard electrode potentials**

The reaction involves lead and gold.

$Pb^{2+}(aq) + 2e^- \rightleftharpoons Pb(s)$ ($E^\circ$ V $= -0{,}13$ V) $Au^{3+}(aq) + 3e^- \rightleftharpoons Au(s)$ ($E^\circ$ V $= +1{,}50$ V)

**Step 2: Which metal is more likely to be reduced, which is more likely to be oxidised?**

The E° of lead is a small, negative value and the E° of gold is a large, positive number. Therefore lead is more easily oxidised than gold, and gold is more easily reduced than lead.

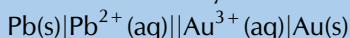
**Step 3: Determine which metal is the cathode and which is the anode**

Oxidation is loss at the anode, therefore lead is the anode.

Reduction is gain at the cathode, therefore gold is the cathode.

**Step 4: Represent the cell using standard cell notation**

The anode is always written on the left, the cathode on the right.

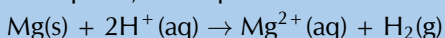
$Pb(s)|Pb^{2+}(aq)||Au^{3+}(aq)|Au(s)$

**Step 5: Calculate the cell potential**

$E^\circ_{(cell)} = E^\circ_{(cathode)} - E^\circ_{(anode)}$

$E^\circ_{(cell)} = E^\circ_{(gold)} - E^\circ_{(lead)} = +1{,}50 - (-0{,}13) = +1{,}63$ V

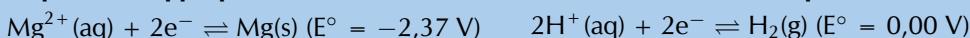
**Worked example 11: Calculating the EMF of a cell**

***QUESTION***

Calculate the cell potential of the electrochemical cell in which the following reaction takes place, and represent the cell using standard notation.

$Mg(s) + 2H^+(aq) \rightarrow Mg^{2+}(aq) + H_2(g)$

***SOLUTION***

**Step 1: Find appropriate reactions on the table of standard electrode potentials**

$Mg^{2+}(aq) + 2e^- \rightleftharpoons Mg(s)$ ($E^\circ = -2{,}37$ V) $2H^+(aq) + 2e^- \rightleftharpoons H_2(g)$ ($E^\circ = 0{,}00$ V)

**Step 2: Which element is more likely to be reduced, which is more likely to be oxidised?**

The E° of magnesium is a more negative value than the E° of hydrogen. Therefore magnesium is more easily oxidised than hydrogen, and hydrogen is more easily reduced than magnesium.

**Step 3: Determine which metal is the cathode and which is the anode**

Oxidation is loss at the anode, therefore magnesium is the anode.

Reduction is gain at the cathode, therefore hydrogen is the cathode reaction.

**Step 4: Represent the cell using standard notation**

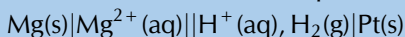
The anode is always written on the left, the cathode on the right. The hydrogen

**TIP**

| Spontaneous |
| --- |
| positive EMF |
| **Non-spontaneous** |
| negative EMF |

Table 13.4: Using EMF to determine cell spontaneity.

**FACT**
One can perform experiments to predict whether a reaction will be spontaneous or not. It turns out that the sign of the EMF is equivalent to whether a cell reaction is spontaneous or not. Those reactions that are spontaneous have a positive EMF and those reactions that are non-spontaneous have a negative EMF.

electrode includes an inert platinum plate.
$Mg(s)|Mg^{2+}(aq)||H^{+}(aq), H_2(g)|Pt(s)$

**Step 5: Calculate the cell potential**

$E_{(cell)} = E^{\circ}_{(cathode)} - E^{\circ}_{(anode)}$

$E_{(cell)} = E^{\circ}_{(hydrogen)} - E^{\circ}_{(magnesium)} = 0,00 - (-2,37) = +2,37\text{ V}$

**Exercise 13 – 8: Standard electrode potentials**

1. In your own words, explain what is meant by the 'electrode potential' of a metal.
2. Calculate the EMF for each of the following standard electrochemical cells:
   a) $Mn(s)|Mn^{2+}(aq)||H^{+}(aq), H_2(g)|Pt(s)$
   b) $Fe(s)|Fe^{3+}(aq)||Fe^{2+}(aq)|Fe(s)$
   c) $Cr(s)|Cr^{2+}(aq)||Cu^{2+}(aq)|Cu(s)$
   d) $Pb(s)|Pb^{2+}(aq)||Hg^{2+}(aq)|Hg(\ell)$
3. Given the following two half-reactions:
   $Fe^{3+}(aq) + e^{-} \rightleftharpoons Fe^{2+}(aq)$
   $MnO_4^{-}(aq) + 8H^{+}(aq) + 5e^{-} \rightleftharpoons Mn^{2+}(aq) + 4H_2O(\ell)$
   a) Give the standard electrode potential for each half-reaction.
   b) Which reaction takes place at the cathode and which reaction takes place at the anode?
   c) Represent the electrochemical cell using standard notation (the cathode and anode reactions take place at inert platinum electrodes).
   d) Calculate the EMF of the cell
4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 282M 2a. 282N 2b. 282P 2c. 282Q 2d. 282R 3. 282S

## Spontaneity ESCRN

You can see from the table of reduction potentials (Table 13.2) that different metals have different reactivities. Some are reduced more easily than others. You can also say that some are oxidised more easily than others.

For example, copper ($E^{\circ} = +0,34$ V) is more easily reduced than zinc ($E^{\circ} = -0,76$ V). Therefore, if a reaction involves the reduction of copper and the oxidation of zinc, it will occur spontaneously. If, however, it requires the oxidation of copper and the reduction of zinc, it will not occur spontaneously.

To predict whether a reaction occurs spontaneously you can look at the sign of the EMF value for the cell. If the EMF is **positive** then the reaction is **spontaneous**. If the EMF is **negative** then the reaction is **not spontaneous**.

Look at the following example to help you to understand how to predict whether a reaction will take place spontaneously or not.

In the reaction $Pb^{2+}(aq) + 2Br^{-}(aq) \rightleftharpoons Br_2(\ell) + Pb(s)$ the two half-reactions are as follows:

$Pb^{2+}(aq) + 2e^{-} \rightleftharpoons Pb(s)$ $(E^\circ = -0{,}13\ V)$ $Br_2(\ell) + 2e^{-} \rightleftharpoons 2Br^{-}(aq)$ $(E^\circ = +1{,}06\ V)$

EMF = E°(reduction half-reaction) - E°(oxidation half-reaction)

EMF = E°(lead) - E°(bromide)

EMF = $-0{,}13$ V - 1,06 = $-1{,}19$ V

The sign of the EMF is negative, therefore this reaction will not take place spontaneously. Let's look at the reasoning behind this in more detail.

Look at the electrode potential for the first half-reaction. The negative value shows that lead loses electrons more easily than bromine, in other words it is easily oxidised. However, in the original equation, lead ions ($Pb^{2+}$) are being reduced. This part of the reaction is not spontaneous.

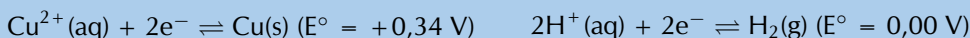
For the second half-reaction the positive electrode potential value shows that bromine is more easily reduced than lead: bromine will more easily gain electrons to become $Br^{-}$. This is not what is happening in the original equation and therefore this is also not spontaneous.

It therefore makes sense that the reaction will not proceed spontaneously.

**Worked example 12: Determining spontaneity**

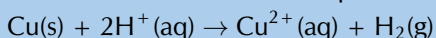
***QUESTION***

Will copper react with dilute sulfuric acid ($H_2SO_4$)? You are given the following half-reactions:

$Cu^{2+}(aq) + 2e^{-} \rightleftharpoons Cu(s)$ $(E^\circ = +0{,}34\ V)$ $2H^{+}(aq) + 2e^{-} \rightleftharpoons H_2(g)$ $(E^\circ = 0{,}00\ V)$

***SOLUTION***

**Step 1: Determine the overall equation for this reaction**

The question asked is if copper metal will react with dilute sulfuric acid, therefore the reactants are Cu(s) and $H^{+}(aq)$:

$Cu(s) + 2H^{+}(aq) \rightarrow Cu^{2+}(aq) + H_2(g)$

**Step 2: Which reactant should be oxidised, and which should be reduced?**

$Cu(s) \rightarrow Cu^{2+}(aq) + 2e^{-}$, therefore copper needs to be oxidised.

$2H^{+}(aq) + 2e^{-} \rightarrow H_2(g)$, therefore hydrogen ions needs to be reduced.

**Step 3: Predict whether the reaction will be spontaneous or non-spontaneous**

Copper has a larger, positive E° than hydrogen. Therefore copper is more easily reduced than hydrogen, and hydrogen is more easily oxidised than copper.

The reaction is non-spontaneous.

**Step 4: Calculate the EMF of the cell**

$E^{\circ}_{(cell)} = E_{(reduction)} - E_{(oxidation)}$

$E^{\circ}_{(cell)} = E_{(hydrogen\ ions)} - E_{(copper)} = 0{,}00\ V - (+0{,}34\ V) = -0{,}34\ V$

**Step 5: Is the reaction spontaneous?**

The EMF is negative, therefore the reaction is non-spontaneous.

### Worked example 13: Determining spontaneity

***QUESTION***

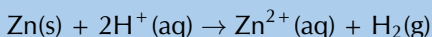
Will zinc react with dilute hydrochloric acid (HCl)? You are given the following half-reactions:

$Zn^{2+}(aq) + 2e^- \rightleftharpoons Zn(s)$ ($E^\circ = -0,76$ V) $2H^+(aq) + 2e^- \rightleftharpoons H_2(g)$ ($E^\circ = 0,00$ V)

***SOLUTION***

**Step 1: Determine the overall equation for this reaction**

The question asked is if zinc metal will react with dilute hydrochloric acid, therefore the reactants are Zn(s) and $H^+$:

$Zn(s) + 2H^+(aq) \rightarrow Zn^{2+}(aq) + H_2(g)$

**Step 2: Which reactant should be oxidised, and which should be reduced?**

$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$, therefore zinc needs to be oxidised.

$2H^+(aq) + 2e^- \rightarrow H_2(g)$, therefore hydrogen ions need to be reduced.

**Step 3: Predict whether the reaction will be spontaneous or non-spontaneous**

Zinc has a larger, negative E° than hydrogen. Therefore zinc is more easily oxidised than hydrogen, and hydrogen is more easily reduced than copper.

The reaction is spontaneous.

**Step 4: Calculate the EMF of the cell**

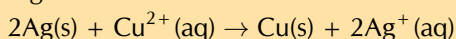
$E^\circ_{(cell)} = E_{(reduction)} - E_{(oxidation)}$

$E^\circ_{(cell)} = E_{(hydrogen\ ions)} - E_{(zinc)} = 0,00\text{ V} - (-0,76\text{ V}) = +0,76\text{ V}$

**Step 5: Is the reaction spontaneous?**

The EMF is positive, therefore the reaction is spontaneous.

### Exercise 13 – 9: Predicting spontaneity

1. Will the following reaction take place spontaneously or not? Show all your working.
   $2Ag(s) + Cu^{2+}(aq) \rightarrow Cu(s) + 2Ag^+(aq)$
2. Nickel metal reacts with an acid, $H^+$ (aq) to produce hydrogen gas.
   a) Write an equation for the reaction, using the table of electrode potentials.
   b) Predict whether the reaction will take place spontaneously. Show your working.
3. Zinc is added to a beaker containing a solution. Will a spontaneous reaction take place if the solution is:
   a) $Mg(NO_3)_2$ b) $Ba(NO_3)_2$ c) $Cu(NO_3)_2$ d) $Cd(NO_3)_2$
4. State whether the following solutions can be stored in an aluminium container.
   a) $CuSO_4$ b) $ZnSO_4$ c) NaCl d) $Pb(NO_3)_2$
5. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 282T 2. 282V 3a. 282W 3b. 282X 3c. 282Y 3d. 282Z
4a. 2832 4b. 2833 4c. 2834 4d. 2835

## 13.7 Applications of electrochemistry ESCRP

**FACT**
A **fuel cell** converts the chemical potential energy produced by the oxidation of fuels (e.g. hydrogen gas, hydrocarbons, alcohols) into electrical energy.

Electrochemistry has a number of different uses, particularly in industry. The principles of cells are used to make **electrical batteries**. In science and technology, a battery is a device that stores chemical energy and makes it available in an electrical form. Batteries are made of electrochemical devices such as one or more galvanic cells or fuel cells. Batteries have many uses including in:

- torches
- electrical appliances such as cellphones (long-life alkaline batteries)
- digital cameras (lithium batteries)
- hearing aids (silver-oxide batteries)
- digital watches (mercury/silver-oxide batteries)
- military applications (thermal batteries)

In this section we are going to look at a few examples of the uses of electrochemistry in industry.

### Electroplating ESCRQ

The electrolytic cell can be used for **electroplating**.

**DEFINITION:** *Electroplating*

The process of coating an electrically conductive object with a thin layer of metal using an electrical current.

Electroplating occurs when an electrically conductive object is coated with a layer of metal using electrical current. Sometimes, electroplating is used to give a metal particular properties or for aesthetic reasons:

- corrosion protection
- abrasion and wear resistance
- the production of jewellery

a) 
b) 

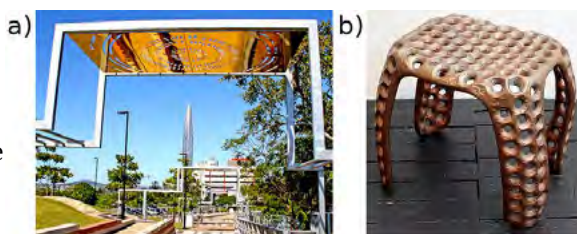



Figure 13.11: **a)** An electroplated piece of aluminium artwork and **b)** a wax stool electroplated in copper.

Electro-refining (also sometimes called **electrowinning**) is electroplating on a large scale. Copper plays a major role in the electrical industry as it is very conductive and is used in electric cables. One of the problems though is that copper must be pure if it is to be an effective current carrier. One of the methods used to purify copper, is electrowinning (copper ore is processed into impure *blister copper*, which is then deposited as pure copper through electroplating). The copper electrowinning process is as follows:

1. A bar of **impure** copper containing other metallic impurities acts as the **anode**.
2. The **cathode** is made up of **pure** copper with few impurities.
3. The electrolyte is a solution of aqueous $CuSO_4$ and $H_2SO_4$.
4. When current passes through the cell, electrolysis takes place:

**FACT**
Remember that electrolytic cells are used to transform reactants into products by turning electric current into chemical potential energy.

- The **impure copper anode** oxidises to form $Cu^{2+}$ ions in solution. The **anode decreases in mass**.

  **Cu(s)** $\rightarrow Cu^{2+}(aq) + 2e^-$

- At the cathode reduction of positive copper ions takes place to produce **pure copper metal**. The **cathode increases in mass**.

  $Cu^{2+}(aq) + 2e^- \rightarrow$ **Cu(s)** (>99% purity)

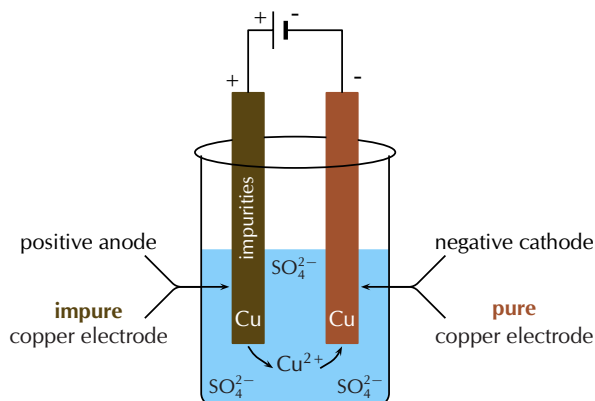



Figure 13.12: A simplified diagram to illustrate what happens during the electrowinning of copper.

5. The other metal impurities do not dissolve (Au(s), Ag(s)) and form a solid sludge at the bottom of the tank or remain in solution (Zn(aq), Fe(aq) and Pb(aq)) in the electrolyte.

## The chloralkali industry ESCRR

The chlorine-alkali (chloralkali) industry is an important part of the chemical industry, which produces **chlorine** and **sodium hydroxide** through the electrolysis of the raw material **brine**. Brine is a saturated solution of sodium chloride (NaCl) that is obtained from natural salt deposits.

**DEFINITION:** *Brine*

A saturated aqueous solution of sodium chloride.

The products of the chloralkali industry have a number of important uses:

**Chlorine** is used:

- to purify water
- as a disinfectant
- in the production of:
  - hypochlorous acid (used to kill bacteria in drinking water)
  - paper, food
  - antiseptics, insecticides, medicines, textiles, laboratory chemicals
  - paints, petroleum products, solvents, plastics (such as polyvinyl chloride)

**Sodium hydroxide** (also known as 'caustic soda') is used to:

- make soap and other cleaning agents
- purify bauxite (the ore of aluminium)

- make paper
- make rayon (artificial silk)

One of the problems of producing chlorine and sodium hydroxide is that when they are produced together the chlorine combines with the sodium hydroxide to form chlorate ($ClO^-$) and chloride ($Cl^-$) ions. This leads to the production of sodium chlorate, NaClO, a component of household bleach.

To overcome this problem the chlorine and sodium hydroxide must be separated from each other so that they don't react. There are three industrial processes that have been designed to overcome this problem. All three methods involve **electrolytic cells**.

**FACT**
In a mercury cell the sodium dissolves in the liquid mercury to form a liquid amalgam of the two metals. This separates the $Cl^-$ and $Na^+$ ions.

1. **The Mercury Cell**
   In the mercury-cell (Figure 13.13):
   - The anode is a carbon electrode suspended from the top of a chamber.
   - The cathode is liquid mercury that flows along the floor of this chamber.
   - The electrolyte is brine (NaCl solution) that is passed through the chamber.
   - When an electric current is applied to the circuit, chloride ions in the electrolyte are oxidised at the anode to form chlorine gas.
     $2Cl^-(aq) \rightarrow Cl_2(g) + 2e^-$
   - At the same time sodium ions are reduced at the anode to solid sodium. The solid sodium dissolves in the mercury making a sodium/mercury amalgam.
     $Na^+(aq) + Hg(\ell) + e^- \rightarrow Na(Hg)$
   - The amalgam is poured into a separate vessel, where it decomposes into sodium and mercury.
   - The sodium reacts with water in the vessel and produces sodium hydroxide and hydrogen gas, while the mercury returns to the electrolytic cell to be used again.
     $2Na(Hg) + 2H_2O(\ell) \rightarrow 2NaOH(aq) + H_2(g) + Hg(\ell)$

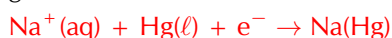
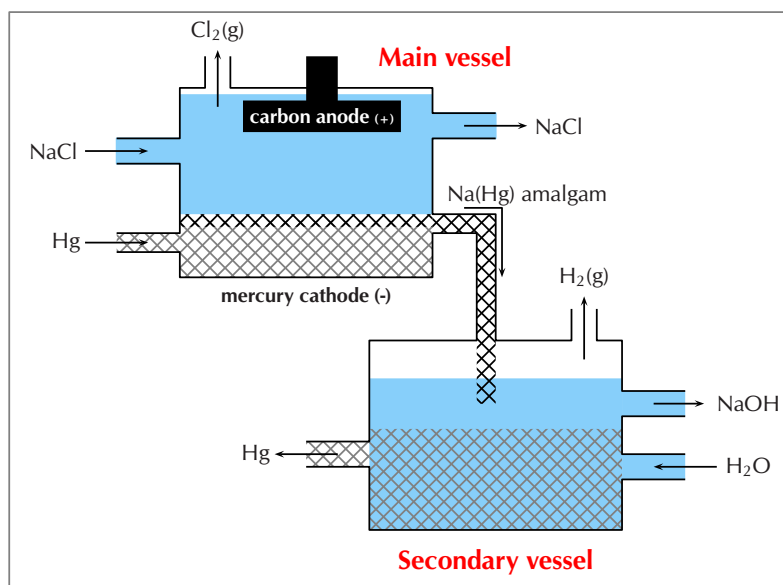
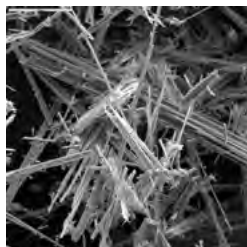



Figure 13.13: The mercury cell.

The following animation gives a good demonstration of how a mercury cell works.

See video: 2836 at www.everythingscience.co.za

**FACT**
To separate the chlorine from the sodium hydroxide, the two half-cells were traditionally separated by a porous asbestos diaphragm, which needed to be replaced every two months.

This was damaging to the environment, as large quantities of asbestos had to be disposed. Asbestos is toxic to humans, and causes cancer and lung problems. Today, the asbestos is being replaced by other polymers, which do not need to be replaced as often, and are not toxic.

This method only produces a fraction of the chlorine and sodium hydroxide that is used by industry as it has certain disadvantages:

- mercury is expensive and toxic
- some mercury always escapes with the brine that has been used
- mercury reacts with the brine to form mercury(II) chloride
- the mercury cell requires a lot of electricity
- although the chlorine gas produced is very pure, mercury has to be removed from the sodium hydroxide and hydrogen gas mixture.

In the past the effluent was released into lakes and rivers, causing mercury to accumulate in fish and other animals feeding on the fish. Today, the brine is treated before it is discharged so that the environmental impact is lower.

2. **The Diaphragm Cell**

In the diaphragm-cell (Figure 13.14):

- a porous diaphragm divides the electrolytic cell into an anode compartment and a cathode compartment
- brine is introduced into the anode compartment and flows through the diaphragm into the cathode compartment
- an electric current is passed through the brine causing the salt's chloride ions and sodium ions to move to the electrodes
- Chlorine gas is produced at the anode
  $2Cl^-(aq) + 2e^- \rightarrow Cl_2(g)$
- At the cathode, sodium ions react with water forming caustic soda (NaOH) and hydrogen gas.
  $2Na^+(aq) + 2H_2O(\ell) + e^- \rightarrow 2NaOH(aq) + H_2(g)$
- Some NaCl salt remains in the solution with the caustic soda and can be removed at a later stage.

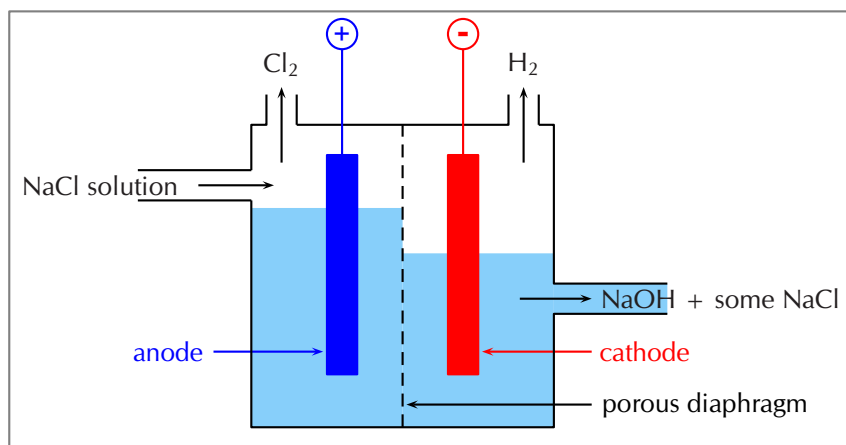



Figure 13.14: The diaphragm cell.

The following animation gives a good demonstration of how a diaphragm cell works.

See video: 2837 at www.everythingscience.co.za

The advantages of the diaphragm cell are:

- uses less energy than the mercury cell
- does not contain toxic mercury

It also has disadvantages however:

- the sodium hydroxide is much less concentrated and not as pure
- the chlorine gas often contains oxygen gas as well

- the process is less cost-effective as the sodium hydroxide solution needs to be concentrated and purified before it can be used

**The Membrane Cell**

The membrane cell (Figure 13.15) is very similar to the diaphragm cell, and the same reactions occur. The main differences are:

3.

- the two electrodes are separated by an ion-selective membrane, rather than by a diaphragm
- the membrane structure allows cations to pass through it between compartments of the cell but does not allow anions to pass through (this has nothing to do with the size of the pores, but rather with the **charge on the ions**)
- brine is pumped into the anode compartment, and only the positively charged sodium ions pass into the cathode compartment, which contains pure water

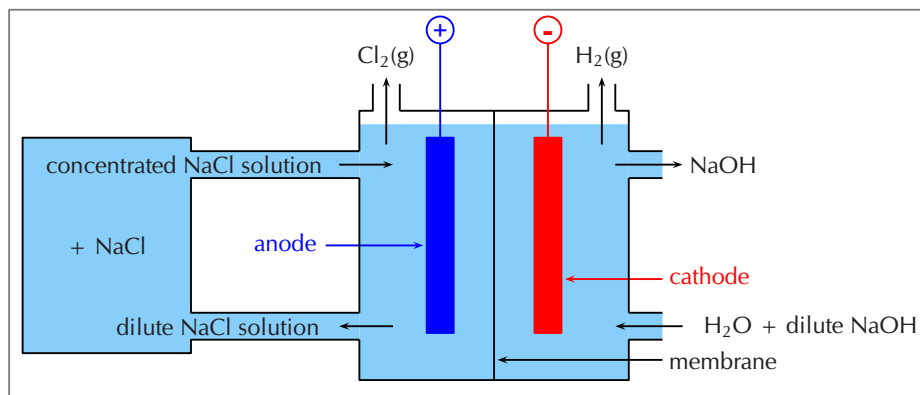



Figure 13.15: The membrane cell.

The following animation gives a good demonstration of how a membrane cell works.

See video: 2838 at www.everythingscience.co.za

- At the **positively charged anode**, $Cl^-$ ions from the brine are oxidised to $Cl_2$ gas.

  $2Cl^-(aq) \rightarrow Cl_2(g) + 2e^-$

- At the **negatively charged cathode**, hydrogen ions in the water are reduced to hydrogen gas.

  $2H_2O(\ell) + 2e^- \rightarrow H_2(g) + 2OH^-$

- The $Na^+$ ions flow through the membrane to the cathode compartment and react with the remaining hydroxide ($OH^-$) ions from the water to form sodium hydroxide (NaOH).

  $Na^+(aq) + OH^-(aq) \rightarrow NaOH(aq)$

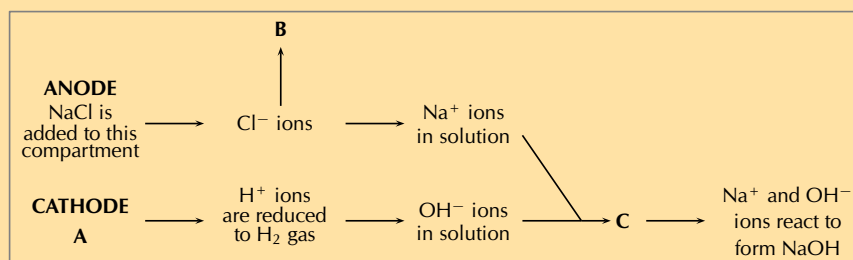
- The chloride ions cannot pass through the membrane, so the chlorine does not come into contact with the sodium hydroxide in the cathode compartment. The sodium hydroxide is removed from the cell. The overall equation is as follows:

  $2NaCl(aq) + 2H_2O(\ell) \rightarrow Cl_2(g) + H_2(g) + 2NaOH(g)$

The advantages of using this method are:

- the sodium hydroxide that is produced is very pure because it is kept separate from the sodium chloride solution
- the sodium hydroxide has a relatively high concentration
- this process uses the least electricity of all three cells
- the cell is cheaper to operate than the other two cells
- the cell does not contain toxic mercury or asbestos

## Exercise 13 – 10: The chloralkali industry

1. Refer to the flow diagram, which shows the reactions that take place in the membrane cell, and then answer the questions that follow.

   a) What liquid is present in the cathode compartment at **A**?

   b) Identify the gas that is produced at **B**.

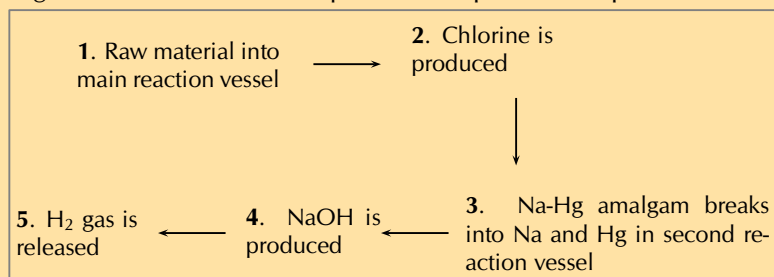
   c) Explain one feature of this cell that allows the $Na^{+}$ and $OH^{-}$ ions to react at **C**.

   d) Give a balanced equation for the reaction that takes place at **C**.

2. Summarise what you have learnt about the three types of cells in the chloralkali industry by completing the table below:

| | **Mercury cell** | **Diaphragm cell** | **Membrane cell** |
|---|---|---|---|
| Main raw material | | | |
| Mechanism of separating $Cl_2$ and NaOH | | | |
| Anode reaction | | | |
| Cathode reaction | | | |
| Purity of NaOH produced | | | |
| Purity of $Cl_2$ produced | | | |
| Energy consumption | | | |
| Environmental impact | | | |
| Cost of production | | | |

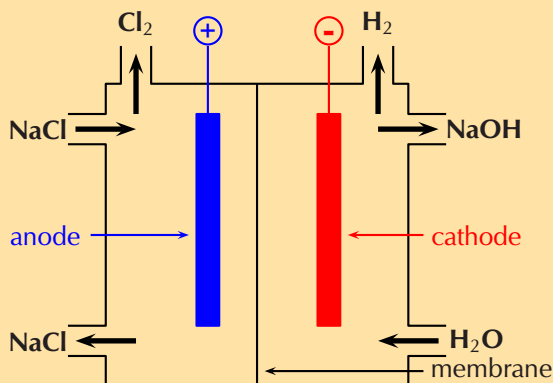
3. The diagram below shows the sequence of steps that take place in the mercury cell.

   **1**. Raw material into main reaction vessel → **2**. Chlorine is produced → **3**. Na-Hg amalgam breaks into Na and Hg in second reaction vessel → **4**. NaOH is produced → **5**. $H_2$ gas is released

   a) Name the 'raw material' in step **1**.

   b) Give the chemical equation for the reaction that produces chlorine gas in step 2.

c) What other product is formed in step 2.

d) Name the reactants in step 4.

4. Approximately 30 million tonnes of chlorine are used throughout the world annually. Chlorine is produced industrially by the electrolysis of brine. The diagram represents a membrane cell used in the production of $Cl_2$ gas.

a) What ions are present in the electrolyte in the left hand compartment of the cell?

b) Give the equation for the reaction that takes place at the anode.

c) Give the equation for the reaction that takes place at the cathode and forms a gas.

d) What ion passes through the membrane while these reactions are taking place?

e) Chlorine is used to purify drinking water and swimming pool water. The substance responsible for this process is the weak acid, hypochlorous acid (HOCl). One way of putting HOCl into a pool is to bubble chlorine gas through the water. Give an equation showing how bubbling $Cl_2(g)$ through water produces HOCl.

f) A common way of treating pool water is by adding 'granular chlorine'. Granular chlorine consists of the salt calcium hypochlorite, $Ca(OCl)_2$. Give an equation showing how this salt dissociates in water. Indicate the phase of each substance in the equation.

(IEB Paper 2, 2003)

5. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 2839 2. 283B 3. 283C 4. 283D

 www.everythingscience.co.za 

**FACT**

Bauxite is a rock that contains a large amount of aluminium oxide ($Al_2O_3$) and aluminium hydroxide ($Al(OH)_3$) as well as many other aluminium containing minerals. Bauxite is the richest source of aluminium when compared with any other common rock, and is the best aluminium ore.

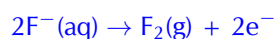
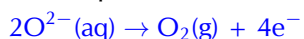
## The extraction of aluminium ESCRS

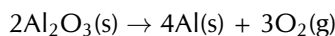
Aluminium is a commonly used metal in industry, where its properties of being both light and strong can be utilised. It is used in the manufacture of products such as aeroplanes and motor cars. The metal is present in deposits of bauxite. Bauxite is a mixture of silicas, iron oxides and hydrated alumina ($Al_2O_3.xH_2O$).

Electrolysis can be used to extract aluminium from bauxite. The process described below produces 99% pure aluminium:

1. Aluminium is melted along with cryolite ($Na_3AlF_6$) which acts as the electrolyte. Cryolite helps to lower the melting point and dissolve the ore.
2. The carbon rod anode provides a site for the oxidation of $O^{2-}$ and $F^-$ ions. Oxygen and fluorine gas are given off at the anode and also result in anode

consumption.

$2O^{2-}(aq) \rightarrow O_2(g) + 4e^-$     $2F^-(aq) \rightarrow F_2(g) + 2e^-$

3. At the cathode cell lining, the $Al^{3+}$ ions are reduced and metal aluminium deposits on the lining. $Al^{3+}(aq) + 3e^- \rightarrow Al(s)$ (99% purity)
4. The $AlF_6^{3-}$ electrolyte is stable and remains in its molten state.

The overall reaction is as follows: $2Al_2O_3(s) \rightarrow 4Al(s) + 3O_2(g)$

The only problem with this process is that the reaction is **endothermic** and large amounts of electricity are needed to drive the reaction. The process is therefore very expensive.

## 13.8 Chapter summary ESCRT

See presentation: 283F at www.everythingscience.co.za

- **Oxidation** is the loss of electrons and **reduction** is the gain of electrons.
- A **redox reaction** is one where there is always a change in the oxidation numbers of the elements that are involved in the reaction.
- It is possible to **balance** redox equations using the half-reactions that take place within the overall reaction.
- An **electrochemical reaction** is one where either a chemical reaction produces an electric current, or where an electric current causes a chemical reaction to take place.
- In a **galvanic cell** a chemical reaction produces a current in the external circuit. An example is the zinc-copper cell.
- An **electrolytic cell** is an electrochemical cell that uses electricity to drive a non-spontaneous reaction. In an electrolytic cell, **electrolysis** occurs, which is a process of separating elements and compounds using an electric current.
- Cells have a number of **components**. They consist of two **electrodes**, which are connected to each other by an external circuit wire.
- In a **galvanic** cell each electrode is placed in a separate container in an **electrolyte** solution. The two electrolytes are connected by a **salt bridge**.
- In an **electrolytic** cell both electrodes are placed in the same container in an **electrolyte** solution.
- One of the electrodes is the **anode**, where **oxidation** takes place. The **cathode** is the electrode where **reduction** takes place.
- In a galvanic cell, the build up of electrons at the anode sets up a potential difference between the two electrodes, and this causes a **current** to flow in the external circuit.
- Standard cell notation for a galvanic cell has the anode on the left and the cathode on the right. For example:
  $Zn(s)|Zn^{2+}(aq)||Cu^{2+}(aq)|Cu(s)$
  $|$ = a phase boundary (solid/aqueous)   $||$ = the salt bridge
- Different metals have different **reaction potentials**. The reduction potential of metals (in other words, their ability to ionise), is recorded in a **table of standard electrode reduction potentials**. The more negative the value, the greater the tendency of the metal to be oxidised. The more positive the value, the greater the tendency of the metal to be reduced.
- The values on the table of standard electrode potentials are measured relative to the **standard hydrogen electrode**.

- The EMF of a cell can be calculated using one of the following equations:
  E°(cell) = E°(reduction half-reaction) - E°(oxidation half-reaction)
  E°(cell) = E°(oxidising agent) - E°(reducing agent)
  E°(cell) = E°(cathode) - E°(anode)
- It is possible to predict whether a reaction is **spontaneous** or not, either by looking at the sign of the cell EMF or by comparing the electrode potentials of the two half-cells.
- Industrial applications of cells include electrolysis (the electrowinning of copper), in the chloralkali industry (**mercury**, **diaphragm** and **membrane** cells), as well as the extraction of metals from ores (e.g. aluminium from bauxite).

### A comparison of galvanic and electrolytic cells

It should be much clearer now that there are a number of differences between *galvanic* and *electrolytic* cells. Some of these differences have been summarised in Table 13.5.

| | Galvanic cell | Electrolytic cell |
|---|---|---|
| Chemical reactions | spontaneous reactions | non-spontaneous reactions |
| Energy changes | Chemical potential energy from chemical reactions is converted to electrical energy | An external supply of electrical energy causes a chemical reaction to occur |
| Anode | is **negative**, oxidation occurs at anode | is **positive**, oxidation occurs at anode |
| Cathode | is **positive**, reduction occurs at cathode | is **negative**, reduction occurs at cathode |
| Cell set-up | two half-cells, one electrode in each, connected by a salt-bridge | one cell, both electrodes in cell, no salt-bridge |
| Electrolyte solution(s) | The electrolyte solutions are kept separate from one another, and are connected by a salt bridge | The cathode and anode are in the same electrolyte |
| Applications | batteries | Electrolysis e.g. of water, NaCl, electroplating |

Table 13.5: A comparison of galvanic and electrolytic cells.

See video: 283G at www.everythingscience.co.za

**Exercise 13 – 11:**

1. A cell is set up. There is a negative charge on the anode.
   a) What type of cell is this?
   b) What type of reaction is occurring at the cathode?
   c) Can the electrodes have the same reaction potential?
   d) Draw and label a diagram of this cell.
2. For each of the following, say whether the statement is **true** or **false**. If it is false, re-write the statement correctly.
   a) The anode in an electrolytic cell has a negative charge.
   b) The reaction $2KClO_3(s) \rightarrow 2KCl(s) + 3O_2(g)$ is an example of a redox reaction.

c) Lead is a stronger oxidising agent than nickel.

3. Sulfur dioxide gas can be prepared in the laboratory by heating a mixture of copper turnings and concentrated sulfuric acid in a suitable flask.
   a) Derive a balanced ionic equation for this reaction using the half-reactions that take place.
   b) Give the E° value for the overall reaction.
   c) Explain why it is necessary to heat the reaction mixture.

4. For each of the following questions, choose the **one correct** answer.
   a) Which one of the following reactions is a redox reaction?
      i. $HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(\ell)$
      ii. $AgNO_3(s) + NaI(s) \rightarrow AgI(s) + NaNO_3(s)$
      iii. $2FeCl_3(aq) + 2H_2O(\ell) + SO_2(aq) \rightarrow H_2SO_4(aq) + 2HCl(aq) + 2FeCl_2(aq)$
      iv. $BaCl_2(s) + MgSO_4(s) \rightarrow MgCl_2(s) + BaSO_4(s)$

      (IEB Paper 2, 2003)
   b) Consider the reaction represented by the following equation:
      $Br_2(\ell) + 2I^-(aq) \rightarrow 2Br^-(aq) + I_2(s)$
      Which one of the following statements about this reaction is correct?
      i. bromine is oxidised
      ii. bromine acts as a reducing agent
      iii. the iodide ions are oxidised
      iv. iodine acts as a reducing agent

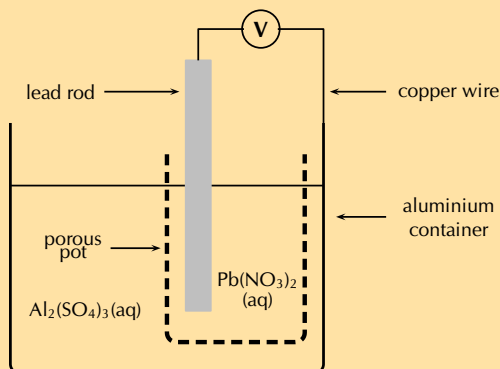
      (IEB Paper 2, 2002)
   c) The following equations represent two hypothetical half-reactions:
      $X_2 + 2e^- \rightleftharpoons 2X^-$ (E° = +1,09 V)
      and $Y^+ + e^- \rightleftharpoons Y$ (E° = −2,80 V)
      Which one of the following substances from these half-reactions has the greatest tendency to lose electrons?
      i. $X^-$
      ii. $X_2$
      iii. Y
      iv. $Y^+$
   d) Which one of the following redox reactions will **not** occur spontaneously at room temperature?
      i. $Mn(s) + Cu^{2+}(aq) \rightarrow Mn^{2+}(aq) + Cu(s)$
      ii. $Fe^{3+}(aq) + 3NO_2(g) + 3H_2O(\ell) \rightarrow Fe(s) + 3NO_3^-(aq) + 6H^+(aq)$
      iii. $Zn(s) + SO_4^{2-}(aq) + 4H^+(aq) \rightarrow Zn^{2+}(aq) + SO_2(g) + 2H_2O(\ell)$
      iv. $5H_2S(g) + 2MnO_4^-(aq) + 6H^+(aq) \rightarrow 5S(s) + 2Mn^{2+}(aq) + 8H_2O(\ell)$
      (DoE Exemplar Paper 2, 2008)

5. In order to investigate the rate at which a reaction proceeds, a learner places a beaker containing concentrated nitric acid on a sensitive balance. A few pieces of copper metal are dropped into the nitric acid.
   a) Use the relevant half-reactions from the table of standard electrode potentials to derive the balanced net ionic equation for the reaction that takes place in the beaker.
   b) What chemical property of nitric acid is illustrated by this reaction?
   c) List three observations that this learner would make during the investigation. (IEB Paper 2, 2005)

6. The following reaction takes place in an electrochemical cell:
   $Cu(s) + 2AgNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + 2Ag(s)$
   a) Give an equation for the oxidation half-reaction.
   b) Which metal is used as the anode?

c) Determine the EMF of the cell under standard conditions.

(IEB Paper 2, 2003)

7. A galvanic cell is constructed by placing a lead rod in a porous pot containing a solution of lead nitrate. The porous pot is then placed in a large aluminium container filled with a solution of aluminium sulfate. The lead rod is then connected to the aluminium container by a copper wire and voltmeter as shown.

a) Define the term *reduction*.

b) Write balanced equations for the reactions that take place at...

i. the cathode

ii. the anode

c) Write a balanced net ionic equation for the reaction which takes place in this cell.

d) In which direction do electrons flow in the copper wire? (Al to Pb or Pb to Al)

e) What are the two functions of the porous pot?

f) Calculate the EMF of this cell under standard conditions.

(IEB Paper 2, 2005)

8. An electrochemical cell is made up of a copper electrode in contact with a copper nitrate solution and an electrode made of an unknown metal M in contact with a solution of $MNO_3$. A salt bridge containing a $KNO_3$ solution joins the two half-cells. A voltmeter is connected across the electrodes. Under standard conditions the reading on the voltmeter is +0,46 V.

a) Sketch the electrochemical cell.

b) Write down the standard conditions which apply to this electrochemical cell.

c) $Cu(s) \rightarrow Cu^{2+}(aq) + 2e^{-}$. Identify the metal M. Show calculations.

d) Use the standard electrode potentials to write down equations for the:

i. anode half-reaction

ii. cathode half-reaction

iii. overall cell reaction

e) What is the purpose of the salt bridge?

(IEB Paper 2, 2004)

9. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 283H 2a. 283J 2b. 283K 2c. 283M 3. 283N 4a. 283P
4b. 283Q 4c. 283R 4d. 283S 5. 283T 6. 283V 7. 283W
8. 283X

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# CHAPTER

## *The chemical industry*

## 14.1 Introduction ESCRV

South Africa has a population of over 50 million people, and this number is increasing every year. Therefore, maintaining healthy crops plays an important role in providing enough food for the nation. Fertilisers are used to provide sufficient nutrients to the soil in order to sustain optimum crop yields. The fertiliser industry is therefore an important chemical industry in South Africa.

Figure 14.1: Farming beetroot in South Africa.

In this chapter we will investigate what fertilisers are, why they are important, how they are produced and what their impact on the environment is.

## 14.2 Nutrients ESCRW

### The importance of nutrients ESCRX

Nutrients are very important for life to exist. An **essential nutrient** is a chemical that a plant needs to be able to grow from a seed and complete its life cycle, but that it cannot produce itself. The same is true for animals. A **macronutrient** is a chemical element that is required in *large quantities* by the plant or animal, whereas a **micronutrient** is only needed in *small amounts* for a plant or an animal to function properly.

**DEFINITION:** *Nutrient*

A nutrient is a chemical substance used for the metabolism and the physiology of an organism and is absorbed from the environment.

In plants, examples of *macronutrients* include carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P) and potassium (K), while *micronutrients* include iron (Fe), chlorine (Cl), copper (Cu) and zinc (Zn).

Nutrients that plants absorb **from the soil** are called *mineral nutrients*. Mineral nutrients have to dissolve in the water in the soil before plants can absorb them. **Non-mineral nutrients** are *not provided by the soil* itself, but from the environment. For example oxygen and hydrogen can be obtained from rain water, while carbon, in the form of carbon dioxide ($CO_2$) is obtained from the air. The source of each of these nutrients for plants, and their function, is summarised in Table 14.1 (for non-mineral nutrients) and Table 14.2 (for mineral nutrients).

| Non-mineral nutrients | Where the nutrient is found (source) | Why the nutrient is needed (function) |
|---|---|---|
| **Carbon (C)** | Carbon dioxide in the air | Component of organic molecules such as carbohydrates, lipids and proteins |
| **Hydrogen (H)** | Water | Component of organic molecules |
| **Oxygen (O)** | Water | Component of organic molecules |

Table 14.1: The source and function of the non-mineral macronutrients in plants.

| Mineral nutrients | Where the nutrient is found (source) | Why the nutrient is needed (function) |
|---|---|---|
| **Nitrogen (N)** | Nitrogen compounds in the soil | Part of plant proteins and chlorophyll, also boosts plant growth |
| **Phosphorus (P)** | Phosphate compounds in the soil | Needed for photosynthesis, blooming and root growth |
| **Potassium (K)** | Potassium compounds in the soil | Cell building, part of chlorophyll, and reduces diseases in plants |

Table 14.2: The source and function of the mineral macronutrients in plants.

Animals need similar nutrients in order to survive. However, since animals do not photosynthesise, they rely on plants to supply them with the nutrients they need. Think of the human diet - we cannot synthesise our own food and so we either need to eat vegetables, fruits and seeds (all of which are direct plant products) or the meat of other animals which would have fed on plants. It is important therefore that plants are always able to access the nutrients that they need so that they will grow and provide food for other forms of life.

**FACT**

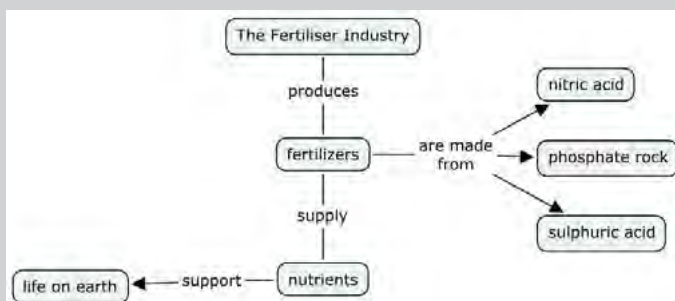
The chemical elements mentioned in this chapter as nutrients really form part of larger nutrient molecules such as proteins or amino acids, carbohydrates, fats, and vitamins.

**TIP**

*Blooming* refers to plants forming flowers. Phosphorus is particularly good for flowering plants.

**Activity: Concept map**

In this activity you are going to make a concept map of this section as a summary that you can use when you study.

1. Read through the content on the first two pages of this chapter.
2. Highlight the most important concepts and words.
3. Use the **words that you have highlighted** to make a concept map of this section. Each concept must be linked to another concept using *linking words*. Below you will find an example that you can use as a starting point for your own concept map.

4. Add to this concept map as you progress through this chapter.

## 14.3 Fertilisers ESCRY

### The role of fertilisers ESCRZ

Refer to the Chemical Industries Resource Pack for more information.

Plants are only able to absorb nutrients from the soil when they are *dissolved* in water so that their root systems can absorb the nutrients. Nitrogen gas ($N_2$) for example, cannot be absorbed in the gas form, and needs to be changed into an ion that is

soluble in water, for example the nitrate ion ($NO_3^-$). In the same way phosphorus is absorbed as phosphate ions ($PO_4^{3-}$).

Plants will grow best in soil that is able to provide sufficient nutrients to them. Natural processes, like the nitrogen cycle, replace nutrients in the soil. However, these natural processes of maintaining soil nutrients take a long time. As populations grow and the demand for food increases, the soil has to supply nutrients faster than the natural processes can sustain. This places more and more strain on the soil to be able to produce a crop.

Often, cultivation practices don't give the soil enough time to recover and to replace the nutrients that have been lost. Today, fertilisers play a very important role in *restoring soil nutrients* so that crop yields can stay high. Some of these fertilisers are **organic** (e.g. compost, manure and fishmeal), which means that they started off as part of something living. Industrial (commercial) fertilisers are **inorganic** (for example ammonium nitrate ($NH_4NO_3$) or super phosphates ($Ca(H_2PO_4)_2$) and have the advantage of being in a *soluble form* that can be absorbed by a plant immediately.

**DEFINITION:** *Fertiliser*

A fertiliser is a chemical compound that is given to a plant to promote growth.

Fertilisers usually provide the three major plant nutrients (nitrogen, phosphorus and potassium). Fertilisers are in general applied to the soil so that the nutrients are absorbed by plants through their roots.

**DEFINITION:** *Organic and inorganic fertilisers*

**Organic** fertilisers are made from *natural products*, like manure or compost. **Inorganic** fertilisers refer to *industrially produced compounds*.

Figure 14.2: Examples of **(a)** organic (compost) and **(b)** inorganic (industrially made) fertilisers indicating the NPK ratio that will be discussed later.

Photos by Kessner Photography on wikipedia and Elvera Viljoen in the UCT Chemical Engineering Chemical Industries Resource pack.

## The NPK ratio ESCS2

Fertiliser packaging contains a set of numbers, for example 6:1:5 (see Figure 14.2). These numbers are called the **NPK ratio**, and they give the mass ratio of nitrogen, phosphorus and potassium in the fertiliser.

The NPK ratio expresses the content of each nutrient as a percentage of N, P and K in this order. A number in brackets after this ratio indicates the percentage by mass of N,

P and K that is present in the fertiliser (what percentage of the total fertiliser is N, P and K). For example:

| **N** | **P** | **K** | |
|---|---|---|---|
| 3 | 1 | 5 | (38) |

38% of the total fertiliser is N, P or K.

% **N**: 3 in every 9 parts of the 38% contains nitrogen (N)

% **P**: 1 in every 9 parts of the 38% contains phosphorus (P)

% **K**: 5 in every 9 parts of the 38% contains potassium (K)

**FACT**

A starter fertiliser is usually used when seeds or young plants are planted. It has high concentrations of nitrogen, to boost plant growth, and phosphorus to boost root growth.

Table 14.3 below gives an idea of the amounts of nitrogen, phosphorus and potassium there are in different types of fertilisers.

| Description | Grade (NPK ratio) |
|---|---|
| Ammonium nitrate | 34:0:0 |
| Urea | 46:0:0 |
| Bone meal | 4:21:1 |
| Seaweed | 1:1:5 |
| Starter fertilisers | 18:24:6 |
| Equal NPK fertilisers | 12:12:12 |
| High N, low P and medium K fertilisers | 25:5:15 |

Table 14.3: Common grades of some fertiliser materials.

Depending on the types of plants you are growing, and the growth stage they are in, you may need to use a fertiliser with a slightly different ratio. For example, if you want to **encourage root growth** in your plant you might choose a fertiliser with a **greater ratio of phosphorus** in it. The main functions of each nutrient (N, P, K) are given in Table 14.4. Remember to refer to Tables 14.1 and 14.2 as well.

| Nutrient | Promotes | When to use |
|---|---|---|
| Nitrogen (N) | leafy plant growth, faster plant growth | on lawns and other plants with lots of green leaves |
| Phosphorus (P) | strong roots, healthy fruit, blooming | on flowers and flower beds |
| Potassium (K) | disease resistance, growth of fruit | on fruit bearing plants |

Table 14.4: The types of plant growth different nutrients promote.

Some countries express the phosphorus content as $P_2O_5$ and potassium content as $K_2O$. South Africa expresses the NPK ratio in terms of the elements present as explained above. The rest of the fertiliser (62%) is made up of fillers, such as gypsum, lime and sand. Other *micronutrients*, such as calcium (Ca), sulfur (S) and magnesium (Mg), are often added to the mixture.

**Worked example 1: NPK ratios**

***QUESTION***

Calculate the mass of nitrogen (N), phosphorus (P) and potassium (K) that is present in 500 g of industrial fertiliser with a NPK ratio of 5:2:3 (40).

***SOLUTION***

**Step 1: Determine the mass of the total nutrients in the fertiliser sample.**

40% of the sample contains nutrients, therefore:

40% of 500 g = 0,4 x 500 g = 200 g which contains nutrients.

**TIP**
If the percentage purity is not given (the number in brackets – e.g. 40 in the worked example above), then you can assume that it is a 100% pure fertiliser and no fillers were added.

**Step 2: Determine the mass of the specific component in the sample**

For every 5 units of nitrogen there are 2 units of phosphorus and 3 units of potassium so the total number of units is 10.

5 of the 10 units are nitrogen: $\frac{5}{10} \times 200\text{ g} = 100\text{ g}$ will be nitrogen (N).

2 of the 10 units are phosphorus: $\frac{2}{10} \times 200\text{ g} = 40\text{ g}$ will be phosphorus (P).

3 of the 10 units are potassium: $\frac{3}{10} \times 200\text{ g} = 60\text{ g}$ will be potassium (K).

**Worked example 2: NPK ratios**

***QUESTION***

Calculate the mole ratio of an industrial fertiliser with the NPK ratio of 5:2:3 (40).

***SOLUTION***

**Step 1: Calculate the mass of N, P and K in a 500 g sample of the fertiliser**

As we are calculating the mole ratio, any amount of fertiliser can be assumed.

As in the previous worked example the ratio is 5:2:3 (40), so the mass of nutrients will be 200 g.

The mass of N $= \frac{5}{10} \times 200\text{ g} = 100\text{ g}$.

The mass of P $= \frac{2}{10} \times 200\text{ g} = 40\text{ g}$.

The mass of K $= \frac{3}{10} \times 200\text{ g} = 60\text{ g}$.

**Step 2: Calculate the number of moles for each element in this sample of fertiliser**

$n = \frac{m}{M}$ The molar mass (M) for N $= 14{,}0\text{ g.mol}^{-1}$

Therefore n for nitrogen $= \frac{100\text{ g}}{14{,}0\text{ g.mol}^{-1}} = 7{,}14\text{ mol}$

M for P $= 31{,}0\text{ g.mol}^{-1}$

Therefore n for phosphorus $= \frac{40\text{ g}}{31{,}0\text{ g.mol}^{-1}} = 1{,}29\text{ mol}$

M for K $= 39{,}1\text{ g.mol}^{-1}$

Therefore n for potassium $= \frac{60\text{ g}}{39{,}1\text{ g.mol}^{-1}} = 1{,}53\text{ mol}$

**Step 3: Determine the mole ratio**

N:P:K mole ratio = 7,14 : 1,29 : 1,53

To get the mole ratio divide all the numbers by the smallest number: 5,5 : 1 : 1,2

The ratio should be expressed as whole numbers: 55 : 10 : 12

**Extension**

N : $P_2O_5$ : $K_2O$

As mentioned previously, in South Africa the NPK ratio is expressed in elemental form, for example the P in the ratio refers to the mass of the element phosphorus (P). How-

ever, in some countries the ratios are expressed in compound form: $N:P_2O_5:K_2O$. Nitrogen still refers to the element nitrogen, but phosphorus and potassium refer to the compounds phosphorus pentoxide ($P_2O_5$) and potassium oxide ($K_2O$). This example will show you how to calculate the mass or moles when a compound ratio is given.

**Worked example 3: NPK ratios in other countries**

***QUESTION***

Calculate the moles of phosphorus (P) in 120 g of a fertiliser with the $N:P_2O_5:K_2O$ mass ratio of 4:3:8 (50).

***SOLUTION***

**Step 1: Calculate the mass of nutrients in the sample of fertiliser**

50% of the sample contains nutrients.

50% of 120 g = 0,5 x 120 g = 60 g which contains nutrients.

**Step 2: Calculate the mass of $P_2O_5$**

The $N:P_2O_5:K_2O$ ratio is 4 : 3 : 8. 4 + 3 + 8 = 15.

3 of the 15 units are $P_2O_5$. The mass of $P_2O_5 = \frac{3}{15} \times 60\text{ g} = 12\text{ g}$.

**Step 3: Calculate the number of moles of $P_2O_5$**

$n = \frac{m}{M}$ $M(P_2O_5) = 2 \times 31{,}0\text{ g.mol}^{-1} + 5 \times 16{,}0\text{ g.mol}^{-1} = 142{,}0\text{ g.mol}^{-1}$

Therefore $n(P_2O_5) = \frac{12\text{ g}}{142{,}0\text{ g.mol}^{-1}} = 0{,}0845\text{ mol}$

**Step 4: Calculate the number of moles of P**

For every 1 mole of $P_2O_5$ there are 2 moles of P atoms.

Therefore, n(P) = 2 x 0,0845 mol = 0,17 mol

**Activity: NPK ratios**

Use Table 14.3, if needed, to answer the following questions:

1. Calculate the mass of phosphorus that is present in 250 g of bone meal.
2. Calculate the moles of nitrogen that are present in 200 g of ammonium nitrate ($NH_4NO_3$).
3. Calculate the mass of potassium that is present in 100 g of seaweed.
4. Calculate the number of moles of potassium in 100 g of a commercial fertiliser with the $N:P_2O_5:K_2O$ mass ratio of 5:1:2 (40).

**Exercise 14 – 1: The role of fertilisers**

1. A starter fertiliser is usually used when seeds or young plants are planted. Use Table 14.3 to answer the following questions.
   a) What is the NPK ratio of a starter fertiliser?
   b) Which nutrient is present in the lowest concentration?

c) Do you think an equal NPK fertiliser will be a good starter fertiliser for new plants? Explain your answer using information from Tables 14.1 - 14.4.

2. Do you think bone meal is a good fertiliser to use for flowering plants? Explain your answer using Tables 14.1 - 14.4.
3. Determine the mass of each of the nutrient components in a 600 g bag of the fertiliser shown in Figure 14.2 (it is produced in South Africa).
4. You have determined that your vegetable garden will need 12 g of nitrogen. The fertiliser you have has 4:2:3 (40) written on the packet. How many grams of fertiliser will you need for your garden?
5. How many moles of potassium is present in 150 g of commercial fertiliser with the $N:P_2O_5:K_2O$ mass ratio of 1:2:5.
6. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 283Y 2. 283Z 3. 2842 4. 2843 5. 2844

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## 14.4 The fertiliser industry ESCS3

### The industrial production of fertilisers ESCS4

For more information on this section refer to the Chemical Industries Resource Pack.

The industrial production of fertilisers involves several processes. Figure 14.3 summarises how a number of different industrial processes are used to manufacture a variety of fertilisers. In the following sections we will discuss the various processes indicated on this diagram.

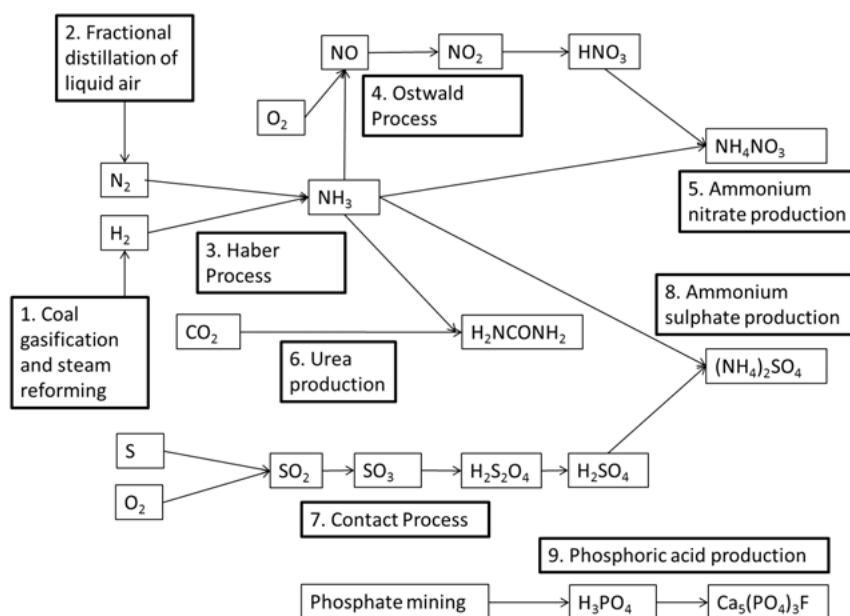
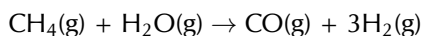



Figure 14.3: The industrial manufacturing of fertilisers.

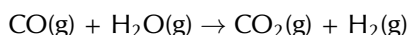
## Producing hydrogen: Coal gasification and steam reforming at Sasol ESCS5

Fossil fuels are the main source of industrial hydrogen. Hydrogen can be generated from **natural gas** or **coal**. These processes are used by Sasol at their Gas-to-Liquid (GTL) and Coal-to-Liquid (CTL) facilities. Hydrogen is usually produced by the **steam reforming** of methane gas (natural gas). At high temperatures (700 – 1100°C), steam ($H_2O$) reacts with **methane** ($CH_4$) in an endothermic reaction to yield **syngas**, a mixture of *carbon monoxide* (CO) and *hydrogen* ($H_2$).

**FACT**
Sasol is an international company that was founded in Sasolburg, South Africa, in 1950. It employs over 34 000 people in at least 38 countries and has interests in synthetic fuels, mining, oil, gas and chemistry.

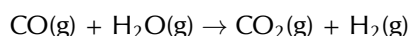
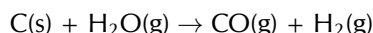
$CH_4(g) + H_2O(g) \rightarrow CO(g) + 3H_2(g)$

During a second stage, which takes place at a lower temperature of about 130°C, the exothermic reaction generates additional hydrogen. This is called a **water gas shift reaction**.

**TIP**
You are not required to know this information in as much depth as is provided here, but the extra information should help your understanding of the subject.

$CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g)$

Essentially, the **oxygen** (O) atom is stripped from the additional water (steam) to oxidise CO to $CO_2$. This oxidation also provides energy to maintain the reaction.

Coal can also be used to produce syngas in a similar way to natural gas. The reactions are shown here:

$C(s) + H_2O(g) \rightarrow CO(g) + H_2(g)$

$CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g)$

Remember that **yield** describes the quantity of product in a container relative to the maximum product possible.

## Obtaining nitrogen: Fractional distillation of liquefied air ESCS6

Fractional distillation is a separation method. It uses the difference in boiling temperatures of the components of a mixture to separate those components.

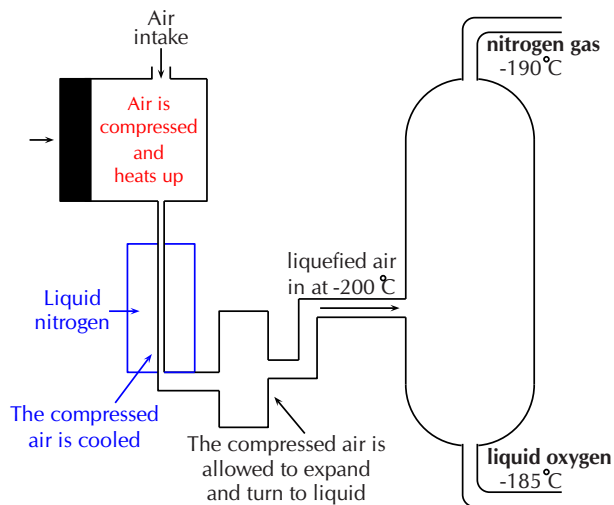



Figure 14.4: A fractional distillation column for the separation of the components of air.

- The mixture is heated to convert the components into the vapour (gas) phase.
- The vapour mixture is then pumped into a tall separation column (called a fractional distillation column), usually at the bottom of the column.
- As the vapour mixture moves up the column and cools, the different components (called fractions) condense as the temperature drops below the various boiling

**FACT**
1 atm = 101,3 kPa

**FACT**
The forward reaction of the Haber process is exothermic, so the forward reaction is favoured by low temperatures. However, low temperatures slow all chemical reactions. So, the Haber process requires high temperatures, and the ammonia is removed as soon as it is formed to prevent it being used in the reverse reaction.

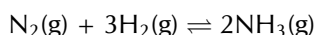
point temperatures.

- These fractions are collected using collection trays.
- The fractions can be removed from the mixture in this way and thus the components are separated.

This process is used to separate the components of air or crude oil. Air is a mixture of gases, mainly nitrogen ($N_2$) and oxygen ($O_2$). Liquefied air (compressed and cooled to $-200°C$) is pumped into the fractional distillation column. Nitrogen gas has the lowest boiling point temperature and is collected at the top of the column (Figure 14.4).

## Producing ammonia: The Haber process ESCS7

Ammonia ($NH_3$) plays an important role in the manufacturing process of fertilisers. The industrial process used to produce ammonia is called the **Haber process**. In this reaction nitrogen gas and hydrogen gas react to produce ammonia gas. The equation for the Haber process is:

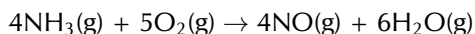
$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$

This reaction takes place in the presence of an iron (Fe) catalyst under high pressure (200 atmospheres (atm)) and temperature (450 – 500°C) conditions.

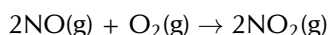
By the 20th century, a number of methods had been developed to *fix* atmospheric nitrogen, in other words to make it usable for plants. Sources of nitrogen for fertilisers included *saltpetre* ($NaNO_3$) from Chile, and guano. Guano is the droppings of seabirds, bats and also seals. In the early 20th century, before the start of the First World War, the Haber process was developed by two German chemists, Fritz Haber and Karl Bosch. They determined what the best conditions were in order to get a high yield of ammonia, and found these to be **high temperature** and **high pressure**. During World War I, the ammonia produced by the Haber process was used to make explosives.

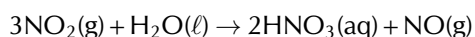
## Producing nitric acid: The Ostwald process ESCS8

The **Ostwald process** is used to produce nitric acid from ammonia. Nitric acid can then be used in reactions that produce fertilisers. Ammonia is converted to nitric acid in a three-step process.

Firstly ammonia is **oxidised** by heating it with oxygen, in the presence of a platinum (Pt) catalyst, to form nitrogen monoxide (NO) and water. This step is strongly **exothermic**, which makes it a useful heat source. The reaction that takes place is:

$4NH_3(g) + 5O_2(g) \rightarrow 4NO(g) + 6H_2O(g)$

In the second step, nitrogen monoxide is oxidised again to yield nitrogen dioxide ($NO_2$) according to the following reaction:

$2NO(g) + O_2(g) \rightarrow 2NO_2(g)$

In step three, nitrogen dioxide is absorbed by water to produce nitric acid ($HNO_3$) as follows:

$3NO_2(g) + H_2O(\ell) \rightarrow 2HNO_3(aq) + NO(g)$

Nitrogen monoxide, also known as nitrogen oxide or nitric oxide, is a by-product of this reaction. The nitrogen monoxide is recycled and the acid is concentrated to the required strength (e.g., for use in further chemical processes).

## Producing ammonium nitrate ESCS9

Nitric acid and ammonia can react together in an acid-base process to form the salt, ammonium nitrate ($NH_4NO_3$). Ammonium nitrate is soluble in water and is often used in fertilisers. The reaction is as follows:

$NH_3(\ell) + HNO_3(\ell) \rightarrow NH_4NO_3(s)$

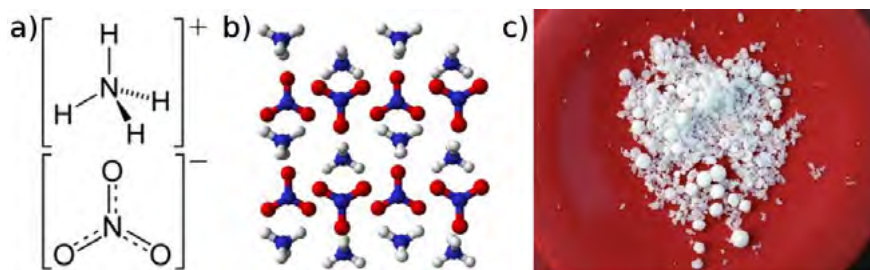
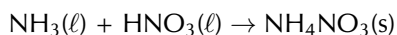



Figure 14.5: Ammonium nitrate presented as **a)** the structural formula, **b)** a three-dimensional molecular representation and **c)** solid crystals.

**FACT**
In 1828, the German chemist Friedrich Wöhler obtained urea by treating silver cyanate (AgOCN) with ammonium chloride ($NH_4Cl$):
$AgOCN + NH_4Cl \rightarrow (NH_2)_2CO + AgCl$
This was the first time an organic compound was artificially synthesised from inorganic starting materials, without the use of living organisms.

## Producing urea ESCSB

Urea ($(NH_2)_2CO$) is a nitrogen-containing compound that is produced on a large scale worldwide. It has the highest nitrogen content (46,4%) of all solid nitrogen-containing fertilisers that are commonly used, and is produced by the reaction of *ammonia* with *carbon dioxide*. Two reactions are involved in producing urea and ammonium carbamate ($H_2NCOONH_4$) is an intermediate product.

$2NH_3(g) + CO_2(g) \rightleftharpoons H_2NCOONH_4(s)$  $H_2NCOONH_4(s) \rightleftharpoons (NH_2)_2CO(aq) + H_2O(\ell)$

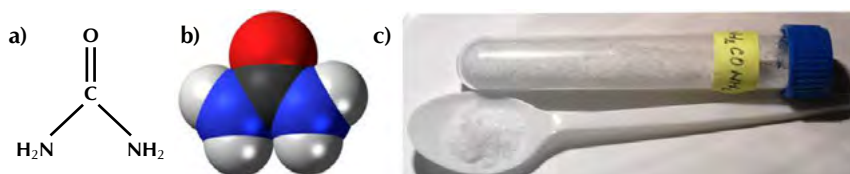
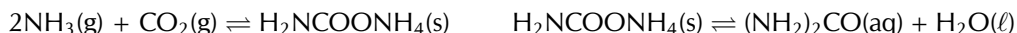
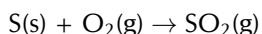
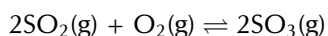



Figure 14.6: Urea presented as **a)** the structural formula, **b)** a space-filling three-dimensional model and **c)** solid crystals.

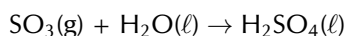
## Producing sulfuric acid: The Contact process ESCSC

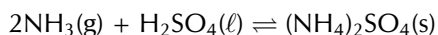
Sulfuric acid ($H_2SO_4$) is produced from sulfur, oxygen and water through the **Contact process**. In the first step, sulfur is burned to produce sulfur dioxide ($SO_2$):

$S(s) + O_2(g) \rightarrow SO_2(g)$

This is then oxidised to sulfur trioxide ($SO_3$) using oxygen in the presence of a vanadium(V) oxide catalyst:

$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$

Finally the sulfur trioxide is treated with water to produce sulfuric acid with a purity of 98 - 99%:

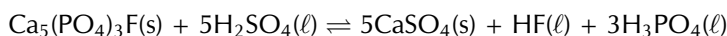
$SO_3(g) + H_2O(\ell) \rightarrow H_2SO_4(\ell)$

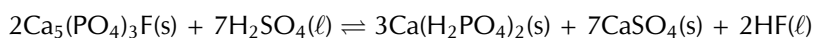
## Producing ammonium sulfate ESCSD

Ammonium sulfate ($(NH_4)_2SO_4$) can be produced industrially through a number of processes, one of which is the reaction of ammonia with sulfuric acid to produce a solution of ammonium sulfate according to the acid-base reaction below:

$$2NH_3(g) + H_2SO_4(\ell) \rightleftharpoons (NH_4)_2SO_4(s)$$

The ammonium sulfate solution is concentrated by evaporating the water until ammonium sulfate crystals are formed.

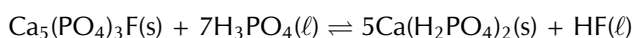
## Producing phosphoric acid and super phosphates ESCSF

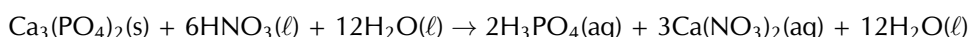
The production of phosphate fertilisers also includes a number of processes. The first is the production of sulfuric acid through the **Contact process**. Sulfuric acid is then used in a reaction with phosphate rock (e.g. fluorapatite ($Ca_5(PO_4)_3F$)) to produce phosphoric acid ($H_3PO_4$). For more information refer to the Chemical Industries Resource Pack.

$$Ca_5(PO_4)_3F(s) + 5H_2SO_4(\ell) \rightleftharpoons 5CaSO_4(s) + HF(\ell) + 3H_3PO_4(\ell)$$

Sulfuric acid can be reacted further with phosphate rock to produce single super phosphates (SSP):

$$2Ca_5(PO_4)_3F(s) + 7H_2SO_4(\ell) \rightleftharpoons 3Ca(H_2PO_4)_2(s) + 7CaSO_4(s) + 2HF(\ell)$$

If phosphoric acid reacts with phosphate rock, triple super phosphates (TSP) are produced:

$$Ca_5(PO_4)_3F(s) + 7H_3PO_4(\ell) \rightleftharpoons 5Ca(H_2PO_4)_2(s) + HF(\ell)$$

## Producing compound fertilisers: The nitrophosphate process ESCSG

The nitrophosphate process is one of the processes used to make complex fertilisers. It involves acidifying calcium phosphate ($Ca_3(PO_4)_2$) with nitric acid to produce a mixture of phosphoric acid and calcium nitrate ($Ca(NO_3)_2$):

$$Ca_3(PO_4)_2(s) + 6HNO_3(\ell) + 12H_2O(\ell) \rightarrow 2H_3PO_4(aq) + 3Ca(NO_3)_2(aq) + 12H_2O(\ell)$$

When calcium nitrate and phosphoric acid react with ammonia, a compound fertiliser is produced.

$$Ca(NO_3)_2(s) + 4H_3PO_4(\ell) + 8NH_3(\ell) \rightarrow CaHPO_4(s) + 2NH_4NO_3(s) + 8(NH_4)_2HPO_4(s)$$

If potassium chloride or potassium sulfate is added, the result will be a NPK fertiliser.

## Advantages and disadvantages of inorganic fertilisers ESCSH

- **Advantages**
  Organic fertilisers generally do not contain high levels of nutrients and might not be suitable to sustain high intensity crop production. **Large scale** agricultural facilities **prefer inorganic** fertilisers as they provide a more accurate control over their nutrient supply. Inorganic fertilisers are supplied in a water-soluble form which ensures that they are easily absorbed by plants. Much less inorganic fertiliser can therefore be applied to have the same result as organic fertilisers.

- **Disadvantages**

  The two major disadvantages of inorganic fertilisers are that:

  - Inorganic fertilisers must be manufactured industrially. This involves cost in terms of both chemicals and the energy involved in the production. Air pollution is also a result of these industrial processes.
  - Nutrients which are **not taken up by plants**, will either accumulate in the soil therefore **poisoning the soil**, or **leach into the ground water** where they will be washed away and accumulate in water sources like dams or underground rivers. This is discussed in more detail in Section 14.6.

**Activity: The industrial production of fertilisers**

Now that you have gone through this section, watch the following animation and go through the worksheet that accompanies it.

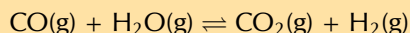
See video: 2845 at www.everythingscience.co.za

Reproductions of the worksheets are given in the teachers guide.

**Exercise 14 – 2: The industrial production of fertilisers**

1. Use the following processes to create your own mind map of the manufacturing of fertilisers:
   - Fractional distillation
   - Steam reforming
   - Haber process
   - Contact process
   - Ostwald process
   - you can, and should, add to this list

   Include what the reactants and the products are for each process and how these link with the other processes involved.
2. Research the process of fractional distillation (from old school science textbooks, from your teacher, or the internet) and write a paragraph on how this process works.
3. The reaction of hydrogen and nitrogen is an exothermic reversible reaction.
   a) Write a balanced equation for this reaction.
   b) Use your knowledge of chemical equilibrium and explain what effect the following will have on this equilibrium reaction:
      i. raising the temperature
      ii. raising the pressure
4. Ammonia and nitric acid react to form the compound A. Compound A is soluble in water and can be used as a fertiliser.
   a) Write down the name and formula for compound A.
   b) What type of reaction takes place to form compound A.
   c) Write a balanced equation for the reaction to form compound A.
   d) Compound A is dissolved in water. Write a balanced ionic equation for this dissolution reaction. Include the state symbols in your equation.
   e) Why is it important for fertilisers to be soluble in water?
   f) Compound A can also be used as an explosive. What precautions need to be taken when this compound is packaged and transported?

5. The following reaction can be used to manufacture hydrogen gas. It is an exothermic redox reaction.
   $CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g)$
   a) Write down the reduction half reaction for this reaction.
   b) Which compound is the reducing agent?
   c) Which compound is the oxidising agent?
   d) Identify two conditions that will ensure a high yield of hydrogen.
6. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 2846  2. 2847  3. 2848  4. 2849  5. 284B

 www.everythingscience.co.za  m.everythingscience.co.za

## 14.5 Alternative sources of fertilisers ESCSJ

Industrial fertilisers have not always been used, and even today many people prefer to use natural fertilisers rather than man-made ones. For more information on alternative sources of fertiliser see the Chemical Industries Resource Pack worksheets here and here.

### Organic fertilisers ESCSK

Organic fertilisers are not manufactured by man, but come from natural sources. Examples are manure, blood and bones, guano, compost and kelp products. Organic fertilisers contain lower levels of nutrients and might take longer than inorganic fertilisers to be absorbed as they generally have to degrade first. The advantage of organic fertilisers is that they increase the organic component of the soil. This improves the physical structure of the soil, which in turn increases the soil's water-holding capacity. The nutrients also tend to be released slower than those of inorganic fertilisers, decreasing their contribution to water pollution.

### Manure ESCSM

Figure 14.7: Horse dung, a type of manure.

Manure is a solid waste product from animals that is widely used as an organic fertiliser in agriculture. It contains **high levels** of *nitrogen, phosphorus, potassium* and other nutrients. Manure decomposes over time through bacterial and microbial action and in the process releases these nutrients into the soil. This **slow release mechanism** is a great benefit to farmers as it limits the leaching of nutrients into the ground water, making it available to plants over a longer period of time. Manure also adds organic matter to the soil, *increasing the quality of the soil itself*.

Plants can only absorb nutrients that are dissolved in water. When manure decomposes, the nitrogen compounds are converted to a form that is soluble in water, for example nitrates ($NO_3^-$). The nitrates are dissolved in the moisture in the soil and plants are then able to absorb the nitrogen compounds through their root system.

**Extension**

Kraal manure

Phosphorus and nitrogen are often the most deficient mineral nutrients in South African soil. The average NPK formula for kraal manure found in the Eastern Cape is 3:1:4 (3). Unfortunately this is not as high in phosphorus, and has a much lower nutrient concentration, than many inorganic fertilisers. However, kraal manure is a much cheaper alternative, is readily available and does not need to be transported as far.

More information on the use of kraal manure can be found on the Agriculture, Forestry and Fisheries website.

## Guano ESCSN

Figure 14.8: A cliff covered in guano.

Figure 14.9: A guano mine off the coast of Peru.

Guano is the excretion of seabirds, bats and seals. Guano consists of *ammonia, uric acid, phosphoric acid, oxalic acid* and *carbonic acid* and also has a high concentration of nitrates. The particularly high levels of phosphorus make this an **effective phosphorus fertiliser**. Guano was mined off the West Coast of South Africa as early as 1666. Since the 1840's, large scale mining of guano caused the reserves to be depleted and mining was stopped by the turn of the century.

## Crop rotation ESCSP

Figure 14.10: A soy bean field.

Figure 14.11: A maize field.

Crop rotation is a farming method that is used to manage the nutrients in soil naturally. When the **same crop** is grown repeatedly in the same place, it eventually **depletes the soil** of specific nutrients. With crop rotation, one type of crop that depletes the soil of

a particular kind of nutrient, is rotated with another type of crop which replaces the depleted nutrient. For example, legumes, like beans or peas, have nodules on their roots which contain nitrogen-fixing bacteria. These bacteria help 'fix' or change nitrogen into a soluble form. Legumes are therefore often alternated with plants requiring nitrogen, and soy beans can therefore be followed by maize.

## Lime ESCSQ

Figure 14.12: Limestone.

Agricultural lime, or crushed limestone, can be used as an alternative fertiliser. Lime **increases the pH of soil**, making the soil less acidic, and **more soluble** for *nitrogen, potassium* and *phosphorus* compounds. These nutrients will therefore be more readily available for absorption by plants.

## Potash ESCSR

Figure 14.13: Potash.

Potash is the **common name** for various mined and manufactured **salts** that contain **potassium** in the water-soluble form. The name is derived from *pot ash*, which was the main method of manufacturing potassium salts before the industrial era. Ashes from a fire were soaked in a pot of water after which the water was filtered out. The water, containing the leached potassium salts, was then evaporated to obtain a white powder known as potash.

Potash is a rich source of potassium and could contain **potassium carbonate** ($K_2CO_3$), **potassium chloride** (KCl), **potassium sulfate** ($K_2SO_4$) or **potassium nitrate** ($KNO_3$). Up to the 19th century potash was manufactured in asheries using wood ashes, but these declined in the late 19th century when large-scale production of potash from mineral salts was established in Germany.

**Activity: Alternative sources of fertilisers**

1. Work on your own to summarise one of the sections on the alternative fertiliser sources. Remember to summarise in your own words.
2. Find all the other learners in your class who have summarised the same topic as you and form a group. Share with your group members what you have summarised.
3. As a group, prepare 3 - 4 sentences on your alternative source of fertiliser. Share your information with the class in 1 - 2 minutes in a debate format.

## 14.6 Fertilisers and the environment ESCSS

The fertiliser industry is a very important industry in South Africa and in the world. It helps provide the nutrients that we need to ensure healthy crops to sustain life on Earth. However, fertilisers can also harm the environment if they are not used in a responsible manner. This section will focus on some of the environmental problems that excessive use of fertilisers can cause.

### Eutrophication ESCST

Eutrophication (Figure 14.14) is the enrichment of an ecosystem with large quantities of chemical compounds, mostly containing the nutrients **nitrogen** and **phosphorus**. Eutrophication is considered a form of **pollution** because it promotes excessive plant growth, favouring certain species over others. In aquatic environments, the rapid growth of certain types of plants can **disrupt the normal functioning of an ecosystem**, causing a variety of problems. Human society is impacted as well, as health-related problems can occur if eutrophic conditions interfere with the treatment of drinking water. Eutrophication can also decrease the resource value of rivers, lakes, and estuaries.

Figure 14.14: An example of the effect of eutrophication (algal bloom).

**DEFINITION:** *Eutrophication*

Eutrophication refers to an over-supply in chemical nutrients in an ecosystem, leading to the depletion of oxygen in a water system through excessive plant growth. These chemical nutrients usually contain nitrogen or phosphorus.

In some cases, eutrophication can be a natural process that occurs very slowly over time. However, it can also be accelerated by certain human activities. **Agricultural runoff**, where excess fertilisers are washed off fields and into ground water, and **sewage**, are two of the major causes of eutrophication. The impacts of eutrophication are the following:

- **A decrease in biodiversity (the number of plant and animal species in an ecosystem)**
  When a system is enriched with nitrogen, plant growth is accelerated. When the number of plants increases in an aquatic system, it can block light from reaching deeper water. Plants also consume oxygen for respiration, depleting the oxygen content of the water, which can cause other organisms, such as fish, to die.
- **Toxicity**
  In certain instances the plants that flourish during eutrophication can be toxic and these toxins may accumulate in the food chain.

Despite these impacts, there are a number of ways to prevent eutrophication from taking place.

**FACT**
A buffer zone is an area that lies between two other areas, for example, a farm and a river. It is an area of land designated for environmental protection.

**FACT**
South Africa's Department of Water Affairs and Forestry has a *National Eutrophication Monitoring Programme*, which was set up to monitor eutrophication in impoundments such as dams, where no monitoring was taking place.

**Prevention of eutrophication:**

- Clean-up measures can directly remove the excess nutrients such as nitrogen and phosphorus from the water.
- Creating buffer zones near farms, roads and rivers can also help. These act as filters and cause nutrients and sediments to be deposited there instead of in the aquatic system.
- Laws relating to the treatment and discharge of sewage can also help to control eutrophication.
- A final possible intervention is nitrogen testing and modelling. By assessing exactly how much fertiliser is needed by crops and other plants, farmers can make sure that they apply only the required amount of fertiliser. This means that there is no excess to run off into neighbouring streams when it rains. This includes a cost benefit for the farmer as they are less likely to waste fertiliser.

**Activity: Dealing with the consequences of eutrophication**

In many cases, the damage from eutrophication is already done. As a class, discuss the following:

1. List all the possible consequences of eutrophication that you can think of.
2. Suggest ways to solve the problems that arise because of eutrophication.
3. Discuss how the public can help to prevent eutrophication.

**Investigation: Fertiliser in your area**

For this investigation you will be working in a group. Your task is to find out what fertilisers are used in your area and whether people know about the impact of fertilisers on the environment, especially the water sources in the area.

1. **Design a survey to find out the following:**
    - Do people use fertilisers in their gardens or the areas around their homes?
    - What type of fertilisers are they using?
    - Why are they using fertilisers?
    - How often do they apply fertilisers?
    - How much fertiliser do they use in each application?
    - Do they use organic or inorganic fertilisers?
    - Which ones do they think are better to use?
    - How do they think fertilisers influence the quality of water in the area?
2. **Collect your data**
   Take the survey to at least 10 people in your area. Record their responses.
3. **Present your findings**
   Present your findings in tables or graphs and write a one-page summary of what you have found.
4. **Interpret your findings**
   Discuss your findings:
    - Answer all the questions that were posed in the beginning of the investigation.
    - Did you find what you thought you would?

- What was different?
- What was the same?
- Why do you think this is the case?

5. **Make recommendations**

   Include some recommendations to people in your neighbourhood regarding the use of fertilisers and their impact on the environment.

   Suggestion: Report your findings in your local newspaper to promote awareness.

## 14.7 Chapter summary ESCSV

- The growth of South Africa's **chemical industry** was largely due to the mining industry, which requires explosives for their operation. One of South Africa's major chemical companies is **Sasol**. Other important examples of chemical industries in the country are the **chloralkali** and **fertiliser** industries.
- The **fertiliser industry** is very important in providing fertilisers with the correct nutrients in the correct quantities to ensure maximum growth for various plants and crops.
- All plants need certain **macronutrients** (e.g. carbon, hydrogen, oxygen, potassium, nitrogen and phosphorus) and **micronutrients** (e.g. iron, chlorine, copper and zinc) in order to survive. Fertilisers provide these nutrients.
- In plants, essential nutrients are obtained from the atmosphere or from the soil.
- Animals also need similar nutrients, but they obtain most of these from plants or plant products. They may also obtain them from other animals, which may have fed on plants during their life.
- **Fertilisers** can be produced industrially using a number of chemical processes: the **Haber process** reacts nitrogen and hydrogen to produce **ammonia**; the **Ostwald process** reacts oxygen and ammonia to produce **nitric acid**; the **Contact process** produces **sulfuric acid**; sulfuric acid then reacts with phosphate rock to produce **phosphoric acid**, after which phosphoric acid reacts with ground phosphate rock to produce fertilisers such as **triple superphosphate**.
- Potassium is obtained from **potash** through a mineral salt extraction process.
- Fertilisers can have a damaging effect on the environment when they are present in high quantities in ecosystems. This can lead to **eutrophication**. A number of preventative actions can be taken to reduce these impacts.

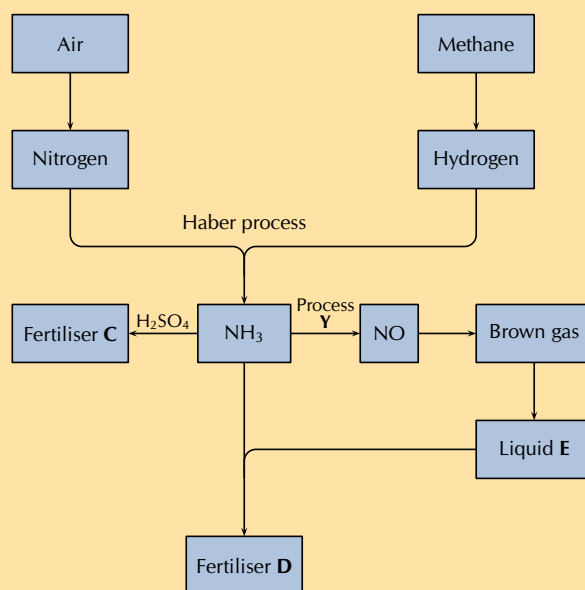
**Exercise 14 – 3:**

1. The following extract comes from an article on fertilisers:

   *A world without food for its people and a world with an environment poisoned through the actions of man are two contributing factors towards a disaster scenario.*

   Do you agree with this statement? Write down at least three arguments to substantiate your answer.
2. There is likely to be a gap between food production and demand in several parts of the world by 2020. Demand is influenced by population growth and urbanisation, as well as income levels and changes in dietary preferences.

While there is an increasing world population to feed, most soils in the world used for large-scale, intensive production of crops lack the necessary nutrients for the crops. This is where fertilisers can play a role.

The flow diagram shows the main steps in the industrial preparation of two important solid fertilisers.

a) How can fertilisers play a role in increasing the soil's ability to produce crops?

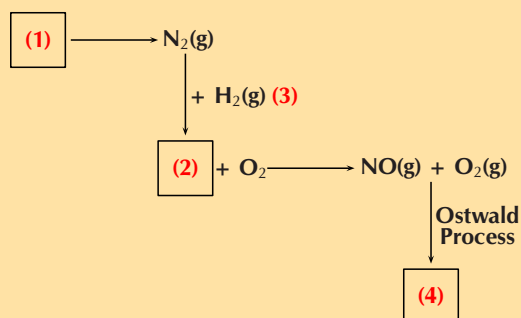
b) Are the processes illustrated by the flow diagram above that of organic or inorganic fertilisers? Give a reason for your answer.

c) Write down the balanced chemical equation for the formation of the brown gas.

d) Write down the name of process **Y**.

e) Write down the chemical formula of liquid **E**.

f) Write down the chemical formulae of fertilisers **C** and **D** respectively.

3. The production of nitric acid is very important in the manufacture of fertilisers. Look at the diagram, which shows part of the fertiliser production process, and then answer the questions that follow.

   a) Name the process at (1).

   b) Name the gas at (2).

   c) Name the process at (3) that produces gas (2).

   d) Name the immediate product at (4).

   e) Name the final product of the Ostwald process (product (4) + $H_2O$).

   f) Name two fertilisers that can be produced from nitric acid.

4. More questions. Sign in at Everything Science online and click 'Practise Science'.

Check answers online with the exercise code below or click on 'show me the answer'.

1. 284D 2. 284C 3. 284F

## 2 Momentum and impulse

**Exercise 2 – 1:**

1. a) $p = 0,16\ \text{kg} \cdot 44,81\text{m} \cdot \text{s}^{-1} = 7,17\ \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$
   b) $p = mv = 0,058\ \text{kg} \cdot 68,39\text{m} \cdot \text{s}^{-1} = 3,97\text{kg} \cdot \text{m} \cdot \text{s}^{-1}$
   c) $p = mv = 0,058\text{kg} \cdot 56,94\text{m} \cdot \text{s}^{-1} = 3,30\ \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$
   d) The ball with the smallest momentum gives you the least chance of being hurt and so you would choose to face Venus.

**Exercise 2 – 2:**

1. $\vec{F} \cdot \Delta t$
2. $\Delta p = 0,9\ \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$ upwards

**Exercise 2 – 3:**

1. $p = -0,06$kg.m/s
2. $p_{\text{total}} = -279\ \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$
3. $p_{\text{total}} = 6113\ \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$ to the south

**Exercise 2 – 4: Collisions**

1. a) $v = 19,09\ \text{m} \cdot \text{s}^{-1}$
   b) $KE_{Ti} = 1\,012\,500$ J
   $KE_{Tf} = 1\,002\,177$ J
   c) The energy difference is permanently transferred into non-elastic deformation during the collision.
   d) Inelastic. Kinetic energy was not conserved in the collision.
2. $\vec{v} = 2{,}5\ \text{m}\cdot\text{s}^{-1}$ in the same direction as the car that was originally travelling at 20 $\text{m}\cdot\text{s}^{-1}$

**Exercise 2 – 5:**

1. $\text{J}\cdot\text{m}\cdot\text{s}^{-1}$
2. a) Take Eastwards as positive.
   For the car:
   $\Delta p = mv_f - mv_i$
   $\Delta p = (1)(-3.4) - (1)(2) = -5.4\ \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$
   For the train:
   $\Delta p = mv_f - mv_i$
   $\Delta p = (2)(1.2) - (2)(-1.5) = 5.4\ \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$
   b) For the car:
   Impulse $= -5.4\ \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$
   For the train:
   Impulse $= 5.4\ \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$
   c) $\Delta t = \frac{5.4}{8} = 0.675\ \text{s}$
3. a) $\Delta p = (0.02)(200) - (0.02)(300) = -2\ \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$
   b) Impulse $= -2\ \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$
   c) $F_{\text{net}} = \frac{2}{0.0001} = 20000\ \text{N}$
4. a) If the bullet leaves the target its total momentum is: $\Delta\vec{p} = (0{,}02)(200) - (0{,}02)(300) = -2\ \text{kg}\cdot\text{m}\cdot\text{s}^{-1}$
   b) If the bullet remains in the target its total momentum is: $\Delta\vec{p} = (0{,}02)(0) - (0{,}02)(300) = -6\ \text{kg}\cdot\text{m}\cdot\text{s}^{-1}$
   c) If the bullet rebounds from the target its total momentum is: $\Delta\vec{p} = (0{,}02)(-200) - (0{,}02)(300) = -10\ \text{kg}\cdot\text{m}\cdot\text{s}^{-1}$
   So the bullet experiences the greatest change in momentum and hence impulse, when it rebounds from the target.
5. a) $\Delta p = mv_f - mv_i = (0.2)(-9) - (0.2)(12) = -4.2\ \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$
   b) $-4.2\ \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$
   c) $F_{\text{net}}\Delta t = \Delta p$
   $F_{\text{net}} = \frac{-4.2}{0.02} = -210\ \text{N}$
6. a) impulse $= 2{,}4\ \text{kg}\cdot\text{m}\cdot\text{s}^{-1}$ into the wall
   b)

$$F = \frac{\Delta\vec{p}}{\Delta t}$$
$$F = \frac{2{,}4}{0{,}5}$$
$$= 4{,}8 \text{ N into the wall}$$

**Exercise 2 – 6:**

1. The canon recoils at 1 $\text{m}\cdot\text{s}^{-1}$ towards the left.
2. We calculate the momentum of the system before and after the collision.
   Before the collision the velocity of the block is 0. The momentum is:
   $\vec{p}_i = m_1\vec{v}_1 + m_2\vec{v}_2 = 0 + (1)(3) = 3\ \text{kg}\cdot\text{m}\cdot\text{s}^{-1}$
   After the collision the momentum is:
   $\vec{p}_f = (m_1 + m_2)\vec{v} = (1 + 0{,}5)(2) = 3\ \text{kg}\cdot\text{m}\cdot\text{s}^{-1}$
   Since the momentum before the collision is the same as the momentum after the collision, momentum is conserved.
3. a) $v_{f1} = 4\ \text{m} \cdot \text{s}^{-1}$ to the left
   b) $\Delta x = 6,02\ \text{m}$ to the left
4. Since the momentum before the ball hits the floor is not equal to the momentum after the ball hits the floor the law of conservation of momentum does not apply to this situation.
   We say that the system is not isolated and that there is a force acting on the ball from outside the system.
5. a) Conservation of momentum
   b) $\vec{v}_f = 14{,}63\ \text{m}\cdot\text{s}^{-1}$
   c) $\vec{F} = 58\,540$ N

**Exercise 2 – 7: Momentum**

1. be projected downwards at the same initial speed as the first piece.
2. The change in momentum of the wall is equal to the change in momentum of the ball.
3. $3\vec{v}$
4. Since their momenta are the same, and the stopping force applied to them is the same, it will take the same time to stop each of the balls.
5. V
6. resultant force
7. $t$
8. $2mv$
9. The units of momentum are: $mv = \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$

   Impulse can be defined as force over total time:

   $F\Delta t = \text{N} \cdot \text{s} = \text{kg} \cdot \text{m} \cdot \text{s}^{-1}$

   This is the same as the units for momentum.
10. a) $\Delta p = F_{\text{net}}\Delta t = \left(3 \times 10^{3}\right)\left(5 \times 10^{-4}\right) = 1.5 \text{ kg} \cdot \text{m} \cdot \text{s}^{-1}$

    b) $\Delta p = mv$

    $1.5 = 0.06v$

    $v = 25 \text{ m} \cdot \text{s}^{-1}$
11. a) Impulse

    b) $250 \text{ m·s}^{-1}$

    c) The area will remain the same because the final velocity and the mass are the same. The duration of the contact between the bat and the ball will be longer as the ball is soft, so the base will be wider. In order for the area to be the same, the height must be lower. Therefore, the player can hit the softer ball with less force to impart the same velocity on the ball.
12. If the front crumples then the force of the collision is reduced. The energy of the collision would go into making the front of the car crumple and so the passengers in the car would feel less force.
13. a) $v_{f2} = -0.6 \text{ m} \cdot \text{s}^{-1} = 0.6 \text{ m} \cdot \text{s}^{-1}$ west

    b) The principle of conservation of linear momentum. The total linear momentum of an isolated system is constant.
14. a) The total linear momentum of an isolated system is constant.

    b) $0{,}4 \text{ m·s}^{-1}$ to the left
15. The magnitude of the change in momentum of the ball is equal to the magnitude of the change in momentum of the Earth.
16. a) $p = mv = (2)(5) = 10 \text{ kg} \cdot \text{m} \cdot \text{s}^{-1}$

    b)

$$\begin{aligned} 0 &= m_1\vec{v}_{1f} + m_2\vec{v}_{2f} \\ -10 &= (50)\vec{v}_{2f} \\ \vec{v}_{2f} &= \frac{-10}{50} \\ &= -0{,}2 \text{ m·s}^{-1} \end{aligned}$$

    $0{,}2 \text{ m·s}^{-1}$ in the opposite direction to the jetty

## 3 Vertical projectile motion in one dimension

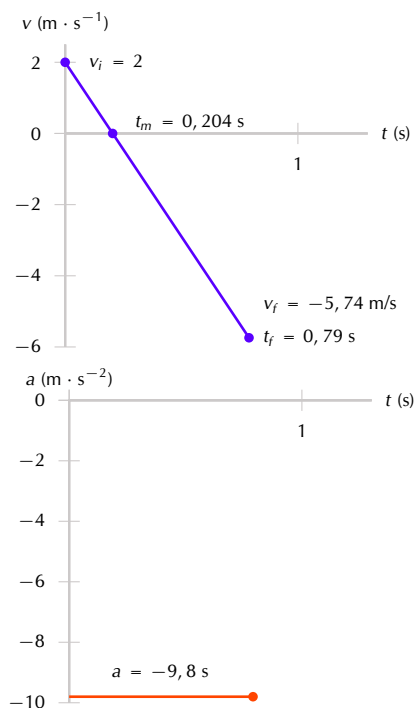
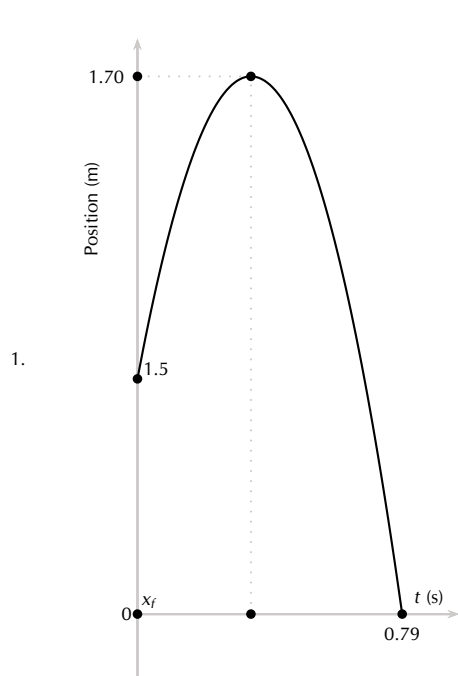
**Exercise 3 – 1: Equations of motion**

1. a) 20,41 m

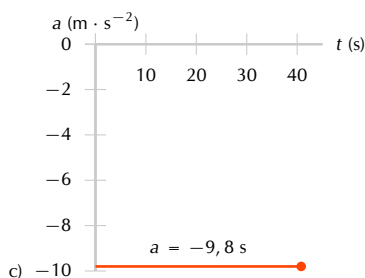
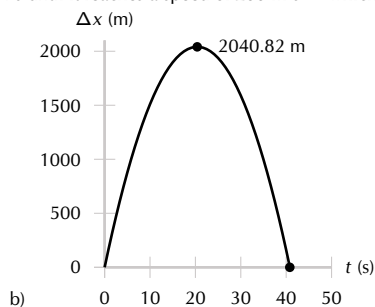
   b) 2,04 s
2. a) $3{,}96 \text{ m·s}^{-1}$ upwards

   b) 0,4 s
3. $20{,}2 \text{ m·s}^{-1}$
4. 125 m

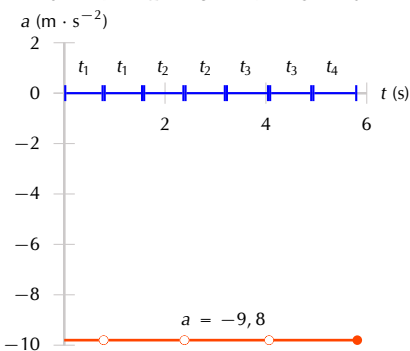
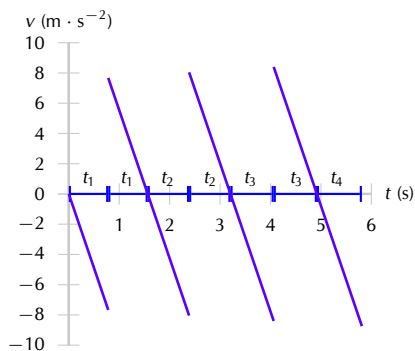
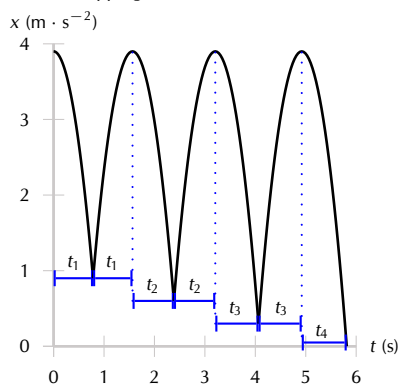
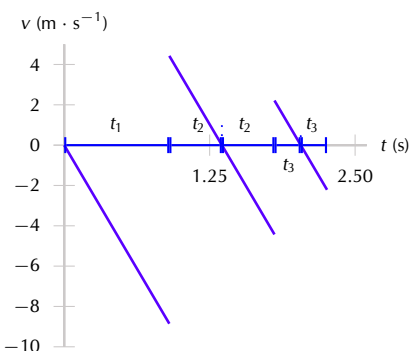
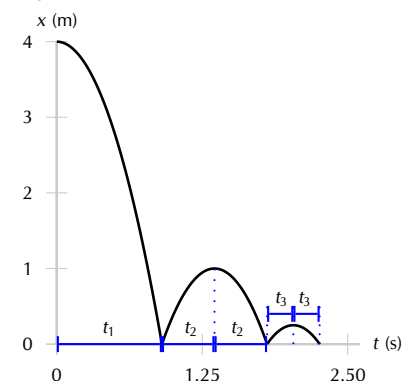
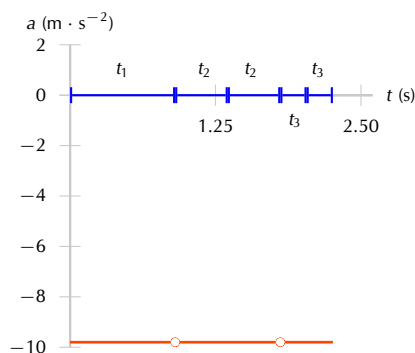
**Exercise 3 – 2: Graphs of vertical projectile motion**

1.

2. a) The bullet moves at a decreasing velocity upwards for 20,4 s. It then stops and drops back down for another 20,4 s until it reaches a speed of 200 m·s$^{-1}$ which is the same speed with which it started.

b)

c)

3. The object starts with an initial height of 0 m, moves upwards for 1 s, then slows and falls back to its starting position where it bounces upwards at a higher velocity, and travels upwards (higher than before) for 2 s, then stops and falls back to its starting position where it bounces upwards again at an even higher velocity, travelling over 3 s to an even higher position, before finally falling back to the ground and stopping.

5.

- $x_1 = 3$ m ; $t_1 = 0{,}782460$ s
- $x_2 = 3{,}3$ m ; $t_2 = 0{,}820651$ s
- $x_3 = 3{,}6$ m ; $t_3 = 0{,}857142$ s
- $x_4 = 3{,}9$ m ; $t_4 = 0{,}892142$ s

6.

**Exercise 3 – 3:**

1. is always downwards
2. A. The same velocity and the same acceleration.
3. b) $u_x = u_y$
4. d) displacement
5. c) the same as when it left the throwers hand.
6. C - the force is constant since the acceleration is constant.
7. The ball will travel upwards, stop at its highest point, and then fall back down to the ground. As it reaches the initial position of 5 metres above the ground, it will be travelling once again at 10 m·s$^{-1}$ but this time in the downwards direction. Taking downwards as the +ve direction:

$$
\begin{aligned}
v_f^2 &= v_i^2 + 2a\Delta x \\
&= (10)^2 + 2(9,8)(5) \\
&= 198 \\
v_f &= \sqrt{198} = 14,07 \text{ m·s}^{-1}
\end{aligned}
$$

8. a) 5 m·s$^{-1}$

   b) the acceleration of the ball

   c)

$$
\begin{aligned}
\text{gradient} &= \frac{\Delta y}{\Delta x} \\
&= \frac{(5 - (-15))}{(2 - 0)} \\
&= 10
\end{aligned}
$$

   10 m·s$^{-2}$

   d) According to the graph, the ball reaches the boy's hand again after 1 second (when the downward speed of 5 m·s$^{-1}$ is the same as its initial upward speed.) Therefore the area under the graph between 1 and 2 seconds (when it reaches its maximum negative velocity) is equal to the remaining distance the ball falls to the ground. The area is equal to 10.

   Distance = 10 m.

   e) It takes 2 s until the ball bounces. Calculate the additional time from bouncing to reach maximum height. **Assume the acceleration is the same as before,** i.e. 10 m·s$^{-2}$.

$$
\begin{aligned}
v_f &= v_i + at \\
t &= \frac{v_f - v_i}{a} \\
&= \frac{0 - 10}{-10} \\
&= 1 \text{ s}
\end{aligned}
$$

   Therefore the total time taken is 3 s.

   f) Calculate the area under the graph for the final 1 second or use equation of motion to find maximum height after the bounce:

$$
\begin{aligned}
\Delta x &= v_i t + \frac{1}{2}at^2 \\
&= (10)(1) + \frac{1}{2}(-10)(1)^2 \\
&= 5 \text{ m}
\end{aligned}
$$

   Therefore the position of the ball, measured from the boy's hand is5 m-5 m = 0 m. In other words, it is the same height as the boy's hand.

9. a) 300 m

   b) 5 m·s$^{-1}$

   c) 600 N

   d) 61,22 kg

10. a) 8,62 m

    b) 1,63 m·s$^{-2}$

# 4 Organic molecules

**Exercise 4 – 1: Representing organic compounds**

1. a) Molecular formula: $C_3H_8$

   b) Molecular formula: $C_5H_{12}$

   c) Molecular formula: $C_2H_6$

2. a) Condensed Structural: $CH_3CHCHCH_3$

   Molecular: $C_4H_8$

   b) Condensed Structural: $CH_2CHCH(CH_3)CH_3$

   Molecular: $C_5H_{10}$

**Exercise 4 – 2: The hydrocarbons**

1. b) $C_nH_{2n-2}$

   c) i. the alkanes

   ii. the alkenes and alkynes

   d) The alkanes

**Exercise 4 – 3: The alcohols**

1. primary
2. tertiary
3. secondary

**Exercise 4 – 4: Haloalkanes**

1. a) $C_nH_{2n+1}X$
   b) Yes

**Exercise 4 – 5: Carbonyl compounds**

1. a) hydroxyl group
   b) carboxylic acid
   c) alcohol and carboxylic acid
2. a) ketone
   c) aldehyde
   d) ester

**Exercise 4 – 6: Functional groups**

1. a) alkane
   b) $C_nH_{2n}$
   c) esters
3. a) Esters
   b) alcohol and carboxylic acid
4. a) alkene
   b) alkane
   c) The product

**Exercise 4 – 8: Naming alkanes**

2. a) 3-methyl**pentane**
   b) 2,4-dimethyl**pentane**
   c) hexane
   d) ethane
   e) 2,3-dimethyl**butane**
   f) 2-methyl**butane**

**Exercise 4 – 9: Naming alkenes**

1. a) pent-1-ene
   b) but-2-ene
   c) but-1,3-diene

**Exercise 4 – 10: Naming alkynes**

2. a) 2,2-dimethylhex-3-yne
   b) prop-1-yne
   c) but-2-yne

**Exercise 4 – 11: Naming hydrocarbons**

2. a) pent-2-ene
   b) 2-ethylbut-1-ene
   c) hexane
   d) but-1-yne
   e) methane
   f) ethyne
   g) propene

**Exercise 4 – 12: Naming haloalkanes**

2. a) 2-iodopropane
   b) 2-bromo-3-methylhexane
   c) 1,4-dichlorooctane
   d) 1-fluoro-2,2-diiodobutane

**Exercise 4 – 13: Naming alcohols**

2. a) butan-2-ol
   b) pentan-2-ol
   c) 4-methylheptan-3,3-diol

**Exercise 4 – 14: Naming aldehydes and ketones**

1. a) pentanal
   b) butan-2-one
   c) hexanal
   d) methanal
   e) pentan-3-one

**Exercise 4 – 15: Naming carboxylic acids**

2. a) ethanoic acid
   b) 4,4-dimethylpentanoic acid
   c) propanoic acid
   d) 2,4-diethylheptanoic acid

**Exercise 4 – 16: Naming esters**

1. a) ethyl ethanoate
   b) pentyl methanoate
   c) propyl hexanoate

**Exercise 4 – 17: Naming carbonyl compounds**

2. a) 3-ethylhexan-2-one
   b) butanal
   c) propyl ethanoate
   d) methanoic acid

**Exercise 4 – 19: Types of intermolecular forces**

2. a) ethane
3. a) B
   b) i. $CH_3CH_2COOH$
      ii. $CH_2(OH)CH_2CH_2CH_3$

**Exercise 4 – 20: Physical properties and functional groups**

1. a) i. butane, but-1-ene
      ii. All except butane and but-1-ene

**Exercise 4 – 21: Physical properties and chain length**

1. c) $C_8H_{16}O_2$
2. a) i. butane, butene
      ii. pentane, pentene, hexane, hexene
4. d) hex-2-yne

**Exercise 4 – 22: Physical properties and branched chains**

1. a) 1-chlorobutane and 2-chloro-2-methylpropane
2. b) hexane, 3-methylpentane and 2,3-dimethylbutane

**Exercise 4 – 23: Physical properties of organic compounds**

1. a) Saturated
   b) aldehydes
   c) i. ethanal
      ii. ethanol
   e) **B**
2. a) butan-1-ol
   b) butan-2-ol
   c) 2-methylpropan-2-ol

**Exercise 4 – 24: Alkanes as fossil fuels**

3. exothermic

**Exercise 4 – 25: Esters**

1. a) methyl ethanoate
   b) octyl ethanoate
   c) hexyl ethanoate
   d) propyl ethanoate
2. acid-catalysed condensation
3. a) butyl ethanoate
   b) butyl pentanoate
   c) butyl heptanoate
   d) butyl methanoate

**Exercise 4 – 26: Addition reactions**

1. b) $CH_3CH_2(Cl)$
2. c) Hydration reaction
3. b) Unsaturated

**Exercise 4 – 27: Elimination reactions**

1. b) The more substituted carbon atom
2. a) saturated
   b) dehydration reaction

**Exercise 4 – 28: Substitution reactions**

1. tertiary alcohol

**Exercise 4 – 29: Addition, elimination and substitution reactions**

1. a) i. addition reaction
      ii. $H_3PO_4$
   c) i. No
      ii. light
   d) i. A. substitution
      ii. A. elimination
2. a) Elimination
4. a) Elimination

**Exercise 4 – 30: Addition polymers**

2. a) polypropene or polypropylene
   b) ethene or ethylene.
   c) chloroethene or vinyl chloride

**Exercise 4 – 32: Polymers**

1. a) propene
2. b) chloroethene or vinyl chloride
   d) Addition
3. b) polylactic acid
   c) Condensation

**Exercise 4 – 33:**

1. a) Alkenes
   b) Hydroxyl group
   c) Carboxylic acid
   d) Ethanoic acid
   e) Ethanol
   f) Ethanol
2. propanoic acid
3. 1,2-dichlorobutane
6. a) i. Alkanes
   ii. Alcohols
   e) 2-methylpropane
7. a) compound 2, ethanol
   b) iv) carboxylic acids
   c) ii) 4,4-dibromobut-1-yne
   d) iii) methyl ethanoate
8. b) ii. methyl ethanoate
   c) i. butane
9. b) 4,4-dimethylhexan-2-one
10. c) Substitution
11. b) $C_nH_{2n+2}$

## 5 Work, energy and power

**Exercise 5 – 1: Work**

1. Normal force:0 J, weight: 0 J, applied force: 50 J.
2. Normal force:0 J, weight: 0 J, frictional force: -50 J.
3. Normal force:0 J, weight: 0 J, frictional force: -50 J, applied force: 50 J.
4. No work is done as all the forces act perpendicular to the direction of displacement.
5. Work done by applied force is 100 J, work done by gravity is -100 J
6. An angle of 55° requires the least amount of work to be done.
7. 1800 J up stairs and 3000 J along passage.
8. 1,30 kJ
9. 50 000 J
10. 5 880 J

**Exercise 5 – 2: Energy**

1.

| position | *EK* | *PE* | v |
|---|---|---|---|
| A | 0 | 50 J | 0 |
| B | 20 | 30 J | 6,3 |
| C | 20 | 30 J | 6,3 |
| D | 40 | 10 J | 8,9 |
| E | 40 | 10 J | 8,9 |
| F | 50 | 0 J | 10 |
| G | 50 | 0 J | 10 |

2. We can assume that the only force acting on the ball is gravity. The speed of the ball would be decreased when it hit the ground if air resistance were taken into account. Air resistance, just like friction on a surface, will be a force opposing the motion and will result in negative work done. By the work energy theorem, this will reduce the net work done on the object falling and therefore reduce the total change in Kinetic Energy.
3. 2,42 $m{\cdot}s^{-1}$

**Exercise 5 – 3: Energy conservation**

1. 9,46 $m{\cdot}s^{-1}$
2. a) 47,65 m
   b) -188 527,5 J
   c) 373,79 N
3. 141,4 $m{\cdot}s^{-1}$

**Exercise 5 – 4: Power**

1. V·A
2. The displacement is 0 and so there is no work done. Since power is the rate at which work is done, the power is also 0.
3. Jack did twice as much work as Jill but the same power.
4. 49 W
5. 1kWh = 1000Wh = 1000Wh × $\frac{3600}{h}$ = 3 600 000 J
6. 1143,33 W

**Exercise 5 – 5:**

1. 16 000 J
2. 2494,67 J
3. Power
4. $\frac{mgh}{t}$
5. $Mgv$
6. The best motor to use is the 3.5 kW motor. The 1.0 kW motor will not be fast enough, and the 5.5 kW motor will be too fast.
7. A box moves at constant velocity across a frictionless horizontal surface.

## 6 Doppler effect

**Exercise 6 – 1: The Doppler effect with sound**

1. The frequency of the sound gradually increases as the train moves towards you. The pitch increases. You would hear a higher pitched sound.
2. 798,73 Hz
3. 51 $m\cdot s^{-1}$
4. The speed of sound in air at -35 degrees celsius is309 $m\cdot s^{-1}$
5. The approach speed is 68 $m\cdot s^{-1}$.

   The frequency observed when moving away is 349,7 Hz.

   A speed of 68 $m\cdot s^{-1}$ or equivalently, 244,8 $km\cdot h^{-1}$, could be reached if the observer was in a high-speed train or a racing car.

**Exercise 6 – 2:**

1. a) The Doppler effect occurs when a source of waves and/or an observer move relative to each other, resulting in the observer measuring a different frequency of the waves than the frequency at which the source is emitting.
   b) Redshift is the shift in the position of spectral lines to longer wavelengths due to the relative motion of a source away from the observer.
   c) Ultrasound or ultra-sonic waves are sound waves with a frequency greater than 20 000 Hz (or 20 kHz).
2. a) 548,4 Hz
   b) 459,5 Hz
   c)
3. a) 15,5 $m\cdot s^{-1}$
   b) As the truck goes by, the frequency goes from higher to lower and the wavelength of the sound waves goes from shorter to longer.
4. 405,7 Hz
5. An instrument called a Doppler flow meter can be used to transmit ultrasonic waves into a person's body. The sound waves will be reflected by tissue, bone, blood etc., and measured by the flow meter. If blood flow is being measured in an artery for example, the moving blood cells will reflect the transmitted wave and due to the movement of the cells, the reflected sound waves will be Doppler shifted to higher frequency if the blood is moving towards the flow meter and to lower frequency if the blood is moving away from the flow meter.
6. 436,8 Hz

## 7 Rate and Extent of Reaction

**Exercise 7 – 2: Reaction rates**

1. b) 5
   c) 3
2. a) $1,99 \times 10^{-5}$ mol.$s^{-1}$
   b) $9,89 \times 10^{-6}$ mol.$s^{-1}$
   c) $2,01 \times 10^{-5}$ mol.$s^{-1}$
3. a) 0,021 mol
   b) 0,00035 mol.$s^{-1}$
   c) i. 0,021 mol
      ii. 0,48 g

**Exercise 7 – 3: Rates of reaction**

1. b) 1 minute
   d) 79 $cm^3$
   e) 15 - 25 min
   f) i. increase

**Exercise 7 – 4: Reaction rates**

1. a) False
   b) True
   c) True
3. b) i. decrease
      ii. increase

**Exercise 7 – 5:**

2. c)
4. b)
5. a) i. $7,5 \times 10^{-4}$ mol.$s^{-1}$
      ii. $7,5 \times 10^{-4}$ mol.$s^{-1}$
   b) i. $1,39 \times 10^{-6}$ mol.$s^{-1}$
      ii. $2,22 \times 10^{-6}$ mol.$s^{-1}$
      iii. $1,6 \times 10^{-6}$ mol.$s^{-1}$
7. e) 1,31 g
   f) 0,022 g.$s^{-1}$

## 8 Chemical equilibrium

**Exercise 8 – 1: Chemical equilibrium**

1. a) ii)
   b) i)
2. a) A + B → C + D
   b) C + D → A + B
   c) reversible

**Exercise 8 – 2: The equilibrium constant**

2. 0,28 mol.dm$^{-3}$
3. 2,25

**Exercise 8 – 3: Equilibrium**

1. b)
2. a) No
   b) lighter
   c) 67,19
3. a) 0,5 mol
   c) Exothermic
   d) decrease
4. a) 5 minutes
   c) 0,44
   g) endothermic
   h) i. no effect
      ii. no effect
      iii. increase

**Exercise 8 – 4: Applying equilibrium principles**

1. a) decreases
   b) reverse
   c) 25 °C

**Exercise 8 – 5:**

2. a)
   b) will change to blue
3. a) change to pink

## 9 Acids and bases

**Exercise 9 – 1: Acids and bases**

2. a) $HCO_3^-$
   b) $H_2O$
   c) $HPO_4^{2-}$
3. a) $H_2O$
   b) HCN
   c) $HCO_3^-$

**Exercise 9 – 3: Types of acids and bases**

1. a) Concentrated
   b) Dilute
2. a) strong
   b) weakly acidic
   c) dilute
3. a) 14,16 mol.dm$^{-3}$
   b) 0,186 mol.dm$^{-3}$
   c) 0,07 mol.dm$^{-3}$
   d) 4,52 mol.dm$^{-3}$

**Exercise 9 – 4: Acids and bases**

1. a) Weak acid
   b) Strong base
   c) Weak base
   d) Strong acid
2. a) Weak acid
   b) Weak base
   c) Strong acid

**Exercise 9 – 5: Calculating pH**

1. a) 13.3
   b) 0.31
2. $1 \times 10^{-12}$ mol.dm$^{-3}$
3. a) basic
   b) 8

**Exercise 9 – 6: Acids and bases**

1. a) 9,00 g
   b) 0,46 mol.dm$^{-3}$

**Exercise 9 – 7:**

2. a) 0,019 mol
   b) $1,14 \times 10^{22}$ atoms
4. 0,26 dm$^3$
5. b) 3,37 g
   c) 13,3
   e) 0,075 mol.dm$^{-3}$

## 10 Electric circuits

**Exercise 10 – 1: Series and parallel networks**

1. a) 0
   b) 23.1
   c) 0.873
   d) 0.521 0.909 0.497
2. a) 2,5 A
   b) 3,75 V
   c) 1,25 A
3. 6 Ω; 2 Ω ; 12 Ω; 7,33 Ω
8. a) 0
   b) 14.4
   c) 0.350
   d) 0.242 0.317 0.292

**Exercise 10 – 2:**

1. So internal resistance is a measure of the resistance of the material that the battery is made of.
2. The emf of a battery is essentially constant because it only depends on the chemical reaction (that converts chemical energy into electrical energy) going on inside the battery. Therefore, we can see that the voltage across the terminals of the battery is dependent on the current drawn by the load. The higher the current, the lower the voltage across the terminals, because the emf is constant. By the same reasoning, the voltage only equals the emf when the current is very small.
3. 0,4 Ω
5. The emf is 10,0 V and the internal resistance is $1{,}1428 \times 10^{-2}$ Ω.
6. The emf is 21,11 V and the internal resistance is 0,55 Ω.
7. The emf is 1,5 V and the internal resistance is 0,6 Ω.

**Exercise 10 – 3:**

1. 20 Ω
4. 0,09 A; 2,25 V; 11,25 V ; 13,50 V
5. $9{,}6 \times 10^{-17}$ J
6. a) 0
   b) 20.8
   c) 1.717
   d) 2.521 1.790 1.571

## 11 Electrodynamics

**Exercise 11 – 1: Generators and motors**

1. An electrical generator is a mechanical device to convert energy from a source into electrical energy.

   An electrical motor is a mechanical device to convert electrical energy from a source into another form energy.
2. Faraday's law says that a changing magnetic flux can induce an emf, when the coil rotates in a magnetic field it is possible for the rotation to change the flux thereby inducing an emf.

   If the rotation of the coil is such that the flux doesn't change, i.e. the surface of the coil remains parallel to the magenetic field, then there will be no induced emf.
5. A current-carrying coil in a magnetic field experiences a force on both sides of the coil that are not parallel to the magnetics field, creating a twisting force (called a torque) which makes it turn. Any coil carrying current can feel a force in a magnetic field. The force is due to the magnetic component of the Lorentz force on the moving charges in the conductor, called Ampere's Law. The force on opposite sides of the coil will be in opposite directions because the charges are moving in opposite directions.
7. Cars (both AC and DC), electricity generation (AC only), anywhere where a power supply is needed.
8. Pumps, fans, appliances, power tools, household appliances, office equipment.

**Exercise 11 – 2: Alternating current**

1. 
   - Easy to be transformed (step up or step down using a transformer).
   - Easier to convert from AC to DC than from DC to AC.
   - Easier to generate.
   - It can be transmitted at high voltage and low current over long distances with less energy lost.
   - High frequency used in AC makes it suitable for motors.
2. The correct answer is C.
3. 

$$\begin{aligned} i &= I_{\max}\sin(2\pi ft + \phi) \\ v &= V_{\max}\sin(2\pi ft) \end{aligned}$$

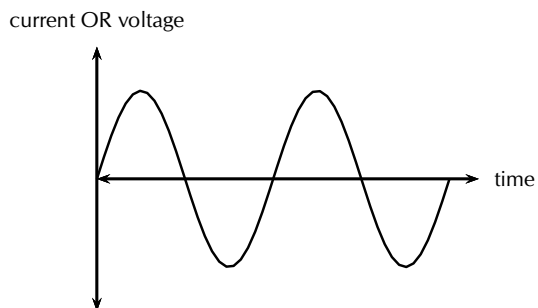
4. The root mean square is the value that we use for AC and is what it's DC equivalent would be.

$$\begin{aligned} I_{rms} &= \frac{I_{\max}}{\sqrt{2}} \\ V_{rms} &= \frac{V_{\max}}{\sqrt{2}} \end{aligned}$$

5. In South Africa the frequency is 50 Hz
6. 

$$\begin{aligned} V_{rms} &= \frac{V_{\max}}{\sqrt{2}} \\ &= \frac{340}{\sqrt{2}} \\ &= 240{,}42 \text{ V} \end{aligned}$$

7. 7.07
8. 188,09 V

9. The graph is the same for both voltage and for current:

**Exercise 11 – 3:**

1. Direct current (DC), which is electricity flowing in a constant direction. DC is the kind of electricity made by a battery, with definite positive and negative terminals. However, we have seen that the electricity produced by some generators alternates and is therefore known as alternating current (AC). So the main difference is that in AC the movement of electric charge periodically reverses direction while in DC the flow of electric charge is only in one direction.
3. While DC motors need brushes to make electrical contact with moving coils of wire, AC motors do not. The problems involved with making and breaking electrical contact with a moving coil are sparking and heat, especially if the motor is turning at high speed. If the atmosphere surrounding the machine contains flammable or explosive vapours, the practical problems of spark-producing brush contacts are even greater.
4. Instead of rotating the loops through a magnetic field to create electricity, as is done in a generator, a current is sent through the wires, creating electromagnets. The outer magnets will then repel the electromagnets and rotate the shaft as an electric motor. If the current is DC, split-ring commutators are required to create a DC motor.
5. In South Africa the frequency is 50 Hz
6. Mr Smith is not correct. He has misunderstood what power is and what Eskom is charging him for.

   AC voltage and current can be described as:

$$i = I_{\text{max}} \sin(2\pi ft + \phi)$$
$$v = V_{\text{max}} \sin(2\pi ft)$$

   This means that for $\phi = 0$, i.e. if resistances have no complex component or if a student uses a standard resistor, the voltage and current waveforms are in-sync.

   Power can be calculated as $P = VI$. If there is no phase shift, i.e. if resistances have no complex component or if a student uses a standard resistor then power is always positive since:

   - when the voltage is negative (−), the current is negative (−), resulting in positive (+) power.
   - when the voltage is positive (+), the current is positive (+), resulting in positive (+) power.
7. $20{,}38 \times 10^{6}$ W

## 12 Optical phenomena and properties of matter

**Exercise 12 – 1: The photoelectric effect**

1. The photoelectric effect its the process whereby an electron is emitted by a metal when light shines on it, on the condition that the energy of the photons (light energy packets) are greater than or equal to the work function of the metal.
2. Two reasons why the observation of the photoelectric effect was significant are (1) that it provides evidence for the particle nature of light and (2) that it opened up a new branch for technological advancement e.g. photocathodes (like in old TVs) and night vision devices.
3. $6{,}25 \times 10^{-22}$ J

## 13 Electrochemical reactions

**Exercise 13 – 1: Oxidation and reduction**

2. a) oxidised
   b) reduced
   c) reduced
   d) oxidised
   e) reduced

**Exercise 13 – 3: Electrochemical reactions**

2. **d)** $Cr_2O_7^{2-}$

**Exercise 13 – 4: Galvanic and electrolytic cells**

1. a) Electrolysis
   b) Yes

**Exercise 13 – 5: Galvanic cells**

1. c) $Fe^{2+}$(aq)
   d) Fe(s)

**Exercise 13 – 6: Table of standard electrode potentials**

1. a) −2,37 V
   b) −0,13 V
   c) −0,25 V
2. a) lithium
   b) cobalt(III)
   c) lithium
   d) Reduction
   e) Reduction
4. a) Chlorine
   b) Calcium

**Exercise 13 – 7: Using standard electrode potentials**

1. No
2. No.
3. Yes.

**Exercise 13 – 8: Standard electrode potentials**

2. a) +1,18 V
   b) −0,4 V
   c) +1,08 V
   d) +0,91 V
3. d) +0,75 V

**Exercise 13 – 9: Predicting spontaneity**

1. not spontaneous
2. b) spontaneous
3. a) not spontaneous
   b) not spontaneous
   c) spontaneous
   d) spontaneous
4. a) cannot be stored
   b) cannot be stored
   c) can be stored
   d) cannot be stored

**Exercise 13 – 10: The chloralkali industry**

1. a) Water and dilute NaOH
   b) Chlorine gas
3. a) sodium chloride
   c) sodium mercury amalgam
   d) sodium mercury amalgam and water
4. d) Sodium ions

**Exercise 13 – 11:**

1. a) Galvanic cell
   b) Reduction
   c) No
2. a) False
   b) True
   c) True
3. b) −0,17 V
4. a) iii)
   b) **iii)**
   c) **iii)**
   d) **ii)**
6. b) copper
   c) 0,46 V
7. f) +1,53 V
8. c) silver

# 14 The chemical industry

**Exercise 14 – 1: The role of fertilisers**

1. a) 18:24:6
   b) potassium (K)
   c) No
2. Yes
4. 67,5 g
5. 1,99 mol

**Exercise 14 – 2: The industrial production of fertilisers**

4. a) ammonium nitrate
   b) Acid-base
5. a) $2H^+ + 2e^- \rightarrow H_2$
   b) Carbon monoxide or CO
   c) Water or $H_2O$

**Exercise 14 – 3:**

1. b) Inorganic fertilisers
   c) $2NO(g) + O_2(g) \rightleftharpoons 2NO_2(g)$
   d) Ostwald process
   e) $HNO_3$
   f) **C** - $(NH_4)_2SO_4$
   **D** - $NH_4NO_3$
3. a) Fractional distillation of air
   b) Ammonia
   c) Haber process
   d) nitrogen dioxide
   e) nitric acid

# List of Definitions

# Image Attribution